Manitoba
Agriculture

Papers
presented at the
33rd ANNUAL

MANITOBA SOCIETY OF SOIL SCIENCE MEETING

January 9 and 10, 1990

This material may not be reproduced without the direct consent of the author(s).

PAPERS PRESENTED

AT THE

33RD ANNUAL

MANITOBA SOCIETY
SOIL SCIENCE MEETING

HOLIDAY INN SOUTH
(Winnipeg)

January 9 and 10, 1990

Officers - 1989-90

President - J. Tokarchuk
Manitoba Agriculture
915-401 York Avenue
Winnipeg, Manitoba
R3C OP8

Vice-President - E. Allerdings
P.F.R.A.
100-317 Main Street South
Dauphin, Manitoba
R7N 1K8

Secretary-Treasurer - K. McGill
Manitoba Soil Testing Laboratory
Department of Soil Science
University of Manitoba
Winnipeg, Manitoba
R3T 2N2

Soil Classification and Interpretation Chairperson - N. Olsen
P.F.R.A.
Box 1047
Morden, Manitoba
ROJ 1GO

Soil Management Chairperson - E. Toews
Manitoba Peatland Farming Association
Box 50
20 First Street South
Beausejour, Manitoba
ROE OCO

Soil Chemistry and Fertility Chairperson - J.C. Yeomans
Department of Soil Science
University of Manitoba
Winnipeg, Manitoba
R3T 2N2

90-06268/4

TABLE OF CONTENTS

PAGE

SOIL CLASSIFICATION AND INTERPRETATION

Physiographic Subdivisions of Manitoba - G.F. Mills, H. Veldhuis and R.G. Eilers 1
Agroecological Resource Areas of Southern Manitoba - R.G. Eilers and G.F. Mills 20
Thermal Regimes of Clay Soils in Manitoba - H. Veldhuis, G.F. Mills and R.G. Eilers 33
Changes in Black Soils Following Forest Invasion of Prairie - L.G. Fuller and D.W. Anderson 47
Effects of Freezing on Sulfate Salts in North Dakota Soils and Wetlands - J.L. Richardson, J.L. Arndt and J.W. Enz 60

SOIL MANAGEMENT

Nitrogen Studies with Wheat under Zero and Conventional Tillage - R.J. Soper and M.R. Grenier 66
Report of the East Central Saskatchewan Soil Conservation Project - G.J. McCallum 80
Sprigging Rhizomatous Grasses in Saline-Alkaline Soils - M.E. Majerus 89
Assessment of Salinity in the Pasquia Soil and Water Management Project - B. Harron and E. Allerdings 99
Selection of Native and Introduced Plants for Saline-Alkaline Soils - M.E. Majerus 111
Simulated Soil Erosion and Crop Productivity - A. Kapoor and C.F. Shaykewich 125
An Assessment of the Alternate Land Use Program for Erosion Control of Steep Sloped Land Along the Riding Mountain Escarpment - W. Hildebrand and V. D'Angiolo 131
Design and Operation of the PFRA Erosion Plots at Miami, Manitoba - J.M.W. Black, D.G. Smith and W.J. Pauls 136
PFRA Erosion Plots, Miami: Interim Results - J.M.W. Black, D.G. Smith and W.J. Pauls 144

SOIL CHEMISTRY AND FERTILITY

Comparison of Models for Describing Corn Yield Response to Nitrogen Fertilizer - M.E. Cerrato and A.M. Blackmer 155
An Expert System for Fertilizer Selection - M. Evans, C. Li, P. Duddridge, M. Wilgosh, R. Mondor and D. Flaten 171
Crop Rotations on the Canadian Prairies - C.A. Grant, L.D. Bailey, C.A. Campbell, R.P. Zentner H.H. Janzen and K.E. Bowren 188

SOIL CHEMISTRY AND FERTILITY (CONTINUED)

PAGE

Effectiveness of Urea and Reactive Layer Coated Urea in Field and Greenhouse Experiments 200
- G. Morden and C.M. Cho

Yield and Nitrogen Uptake by Wheat and Canola Fertilized with Urea and an Urease Inhibitor, Phenylphosphorodiamidate 205
- D.L. DeBeer and J.C. Yeomans

Effects of Nitrapyrin on Corn Yields and Recovery of Ammonium Sulfate at 18 Site-years in Iowa 214
- M.E. Cerrato and A.M. Blackmer

Factors Affecting the Carryover and Bioavailability of Triallate and Trifluralin on Manitoba Soils 233
- G.A. Ross, G.R.B. Webster and C.F. Shaykewich

The Effect of Chloride Fertilizer on Crop Yield 242
- R.M. Mohr and D.N. Flaten

Zn and P Interactions with Soil Nutrients in Flax Growth 248
- C.A. Grant and L.D. Bailey

Long-term Bioavailability of Cu-EDTA and $CuSO_4$ in an Organic Soil 256
- M.D. Thomlinson, G.J. Racz and R.E. Dowbenko

Analysis of Phosphate Transport in Soil 265
- C.M. Cho

Diffusive Transport and Interaction of P, Ca^{++}, K^+ and H^+ Ions in a Model System 272
- O.O. Akinremi and C.M. Cho

The Effect of PB-50 (*Penicillium bilaji* inoculant) on Yield and Phosphorus Uptake by Wheat 283
- J.W. Chambers and J.C. Yeomans

The Effect of N & P and the Inoculation with *Rhizobium* and VA-Mycorrhiza on Lentil Growth and N_2 Fixation 294
- J. Gehrer and R.J. Soper

PHYSIOGRAPHIC SUBDIVISIONS OF MANITOBA

G.F. Mills, H. Veldhuis and R.G. Eilers
Canada-Manitoba Soil Survey

ABSTRACT

The physiography of Manitoba is presented within the framework of major physiographic regions and divisions established for Canada. The classification and criteria used to describe the physical attributes of Manitoba landscapes and associated surface deposits are summarized. A physiographic map has been compiled from soil survey data and from surficial deposit maps and reports. The physical features of four main regions and five major divisions are summarized. Subdivision of these major landscape areas at a scale of 1:2 000 000 is explained with examples. An extended legend is used to describe the physiographic subsections. A brief discussion of use and application of this physiographic overview of Manitoba is presented.

INTRODUCTION

Physiography is a specialization of physical geography that relates to the study of the genesis and evolution of landforms. Landforms are comprised of unconsolidated mineral and organic surface materials that are underlain by older unconsolidated materials or bedrock. These unconsolidated materials are referred to as surface deposits or drift. The major surface deposits in Manitoba are classified according to mode of origin. The most extensive surface materials are derived from groundup bedrock as a result of glacial ice movement and are referred to as till. Materials deposited in lakes are referred to as lacustrine sediments whereas materials deposited by flowing water are referred to as outwash and alluvium. Wind blown materials are referred to as aeolian deposits. Sediments laid down in marine seas are termed marine deposits. Surface deposits in Manitoba can also be classified according to morphology or topographic form, eg., drumlin, esker, end moraine and ground moraine; the character and size of particles eg., clay, silt, sand, gravel and boulders and the combination of these particle sizes as texture, eg. clay, clay loam, sandy loam.

Knowledge of the movement of the continental ice sheet and its effect on the surfaces over which it passed contributes to an understanding of the distribution and properties of surficial deposits and associated soils. The glaciated landscape of Manitoba and the variable composition of surface deposits have had a direct and significant influence on soil development, soil properties and on the resultant land use.

A generalized overview of the nature and extent of surface deposits in Manitoba has been available since 1981 (Manitoba Mineral Resources Division, 1981). General information about landforms and surficial deposits is important for broad scale regional planning whereas information about the nature of soils and their distribution has direct application for land resource planning at both the regional and local level. Physiographic data at both general and more detailed levels of mapping are essential for effective planning, management and use of land and water resources.

A major objective for mapping the physiography of Manitoba is to organize available information about landscapes and associated surficial materials into recognizable map units useful for application at both the regional and local levels of land planning and management. In addition the stratification of landscapes provided by the physiographic map assists in organizing and correlating soil resource data for both generalized and detailed applications.

CRITERIA FOR PHYSIOGRAPHIC SUBDIVISION

The physiographic subdivision of Manitoba is presented within the framework of established physiographic regions and divisions of Canada (Bostock, 1970) and has been correlated with similar separations in Saskatchewan (Acton et. al., 1960). Background information for this physiographic overview was derived from published surficial geology, physiography and pedology references (Figure 1). The level of detail and applicability of this data to the physiographic map varies widely. The most precise description of surficial materials is available for those areas of Manitoba covered by reconnaissance and detail soil surveys. Portions of northern and eastern Manitoba covered by reconnaissance surficial geology maps and by broad scale ecological land surveys are characterized by less detailed information. Finally, for those areas lacking any kind of published surficial geology data, the physiographic map relies on exploratory soil survey and supporting air photo interpretation. Physiographic mapping of these areas of northern Manitoba therefore, is derived from limited groundtruth and consequently is subject to revision as new data becomes available.

The criteria utilized at each level of physiographic classification are summarized in Table 1. The classification system employed is hierarchical in that differentiating criteria at higher levels also apply at lower levels. At the broadest level, physiographic subdivision in Manitoba is according to the age and kind of major bedrock. These separations are in turn divided into regions, each comprising many smaller units representing distinctive change in geologic processes and topography. In general, lower levels of classification portray the greatest degree of homogeneity in terms of landform characteristics and surface deposits.

The two major areas of Manitoba are the central core of ancient Precambrian crystalline rocks forming the "Shield" and the surrounding younger rocks forming the Borderlands (Bostock, 1970). These two areas are subdivided into regions and divisions; the regions and divisions occurring in Manitoba are further separated as sections and subsections on the physiographic map.

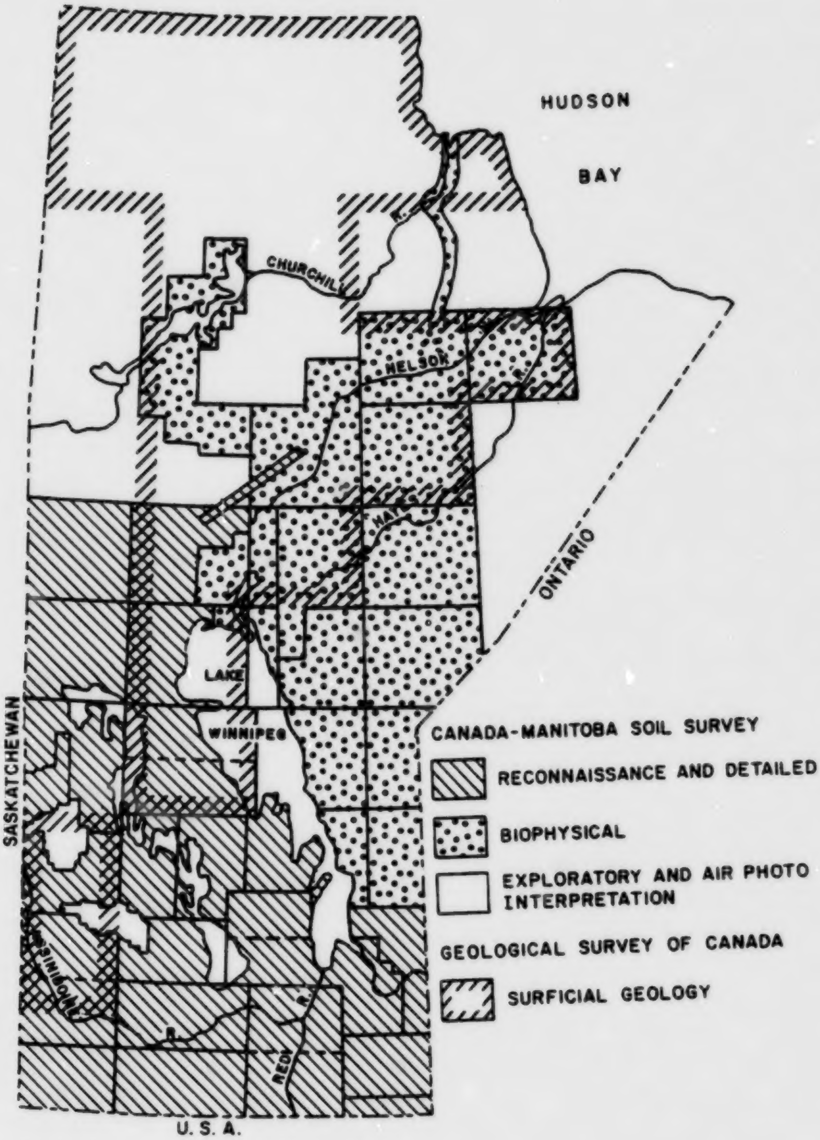

HUDSON
BAY
CHURCHILL
R.
NELSON
HAYES
ONTARIO
LAKE
WINNIPEG
SASKATCHEWAN
ASSINIBOINE
R.
RED
R.
U.S.A.
CANADA-MANITOBA SOIL SURVEY
RECONNAISSANCE AND DETAILED
BIOPHYSICAL
EXPLORATORY AND AIR PHOTO INTERPRETATION
GEOLOGICAL SURVEY OF CANADA
SURFICIAL GEOLOGY

Figure 1. Sources of information.

Table 1. Criteria for physiographic subdivision.

Level of Physiographic Abstraction	Differentiating Criteria
Region	Major bedrock separations recognizing: - origin of bedrock - kind of bedrock and lithology - topography - age
Division	Bedrock subdivisions reflecting: - regional relief and topography - major elevational differences - age (in the Shield only)
Section	Major local topographic and relief differences related to dominant surface deposits recognizing: - uplands - plains - lowlands (extensive plains and lowlands may be subdivided to recognize major watershed differences as well as form and nature of surface deposits)
Subsection	More specific refinement of all section criteria recognizing increased homogeneity in form and composition of local unconsolidated surficial deposits: - mode of origin - texture - depth

Map units at the section level are based on patterns of surface form which repeat over fairly large areas and result genetically from a dominance of one or more kinds of geomorphic processes. Subsections generally depict surface deposits and topographic expression which have less variability and a greater degree of uniformity of composition and form. A single geomorphic process may be dominant. More precise delineation of surface deposits recognized in subsections may be accomplished by mapping at larger scales capable of showing individual materials with a narrow range of texture, depth, and geologic attributes.

PHYSIOGRAPHIC DESCRIPTION

The central core of ancient Precambrian crystalline rocks forming the Shield and the surrounding younger rocks of the Borderlands are divided into four main physiographic regions in Manitoba (Figure 2). The topography and surface deposits of these regions are the basis for separation of five major divisions (Bostock, 1970) which reflect much of the nature of the underlying bedrock and the effects of repeated Pleistocene glaciation.

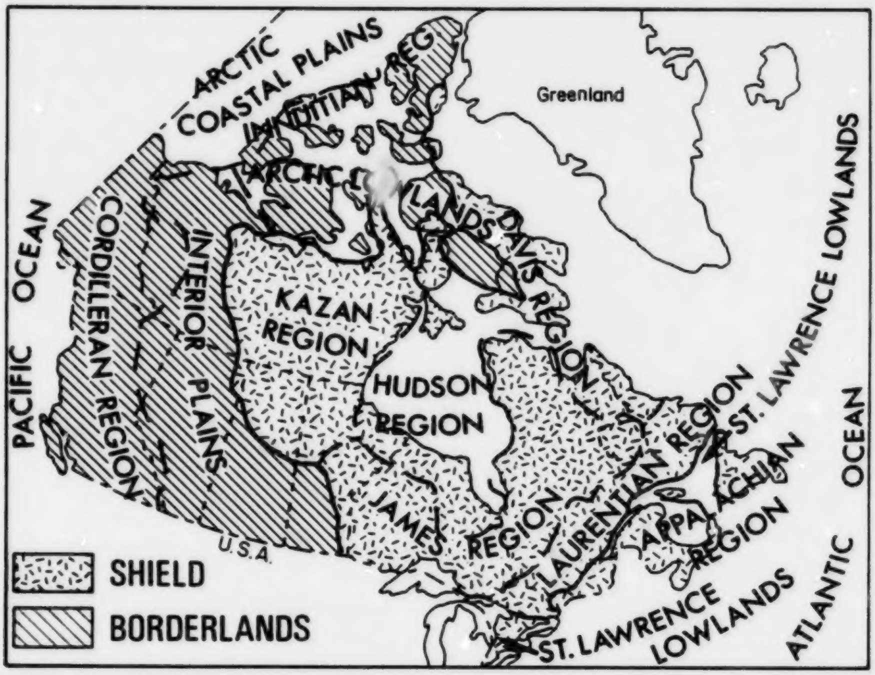

ARCTIC
COASTAL PLAINS
INNUITIAN REG
ARCTIC LOWLANDS
Greenland
DAVIS REGION
PACIFIC OCEAN
CORDILLERAN REGION
INTERIOR PLAINS
KAZAN REGION
HUDSON REGION
JAMES REGION
LAURENTIAN REGION
ST. LAWRENCE LOWLANDS
APPALACHIAN REGION
ATLANTIC OCEAN
U.S.A.
ST. LAWRENCE LOWLANDS
SHIELD
BORDERLANDS

Figure 2. Major physiographic divisions of Canada.

Bedrock Geology

The bedrock of Manitoba falls into two main regions based on age and character; (1) the central Precambrian Shield region and (2) areas in which the Precambrian rock is overlain by younger flat-lying sedimentary rock. The Shield covers 390 000 square kilometers in Manitoba, extending from the southeastern corner to the northwestern part of the province. The area in which sedimentary rock overlies Precambrian rock covers some 260 000 square kilometers (Figure 3).

The Precambrian rocks in Manitoba belong to two geological provinces, the Churchill Province in northwestern Manitoba and the Superior Province of eastern Manitoba.

Younger flat-lying sedimentary rock blankets the Shield in southwestern Manitoba and in the Hudson Bay Lowland. Progressively younger Paleozoic rocks are overlain to the west by Mesozoic rock. The Paleozoic sequence is dominated by carbonate rocks, mainly dolomite, although interbedded shales and sandstones are present.

Mesozoic rocks, predominantly shales with some sandstones overlap the Paleozoic rocks throughout much of southwestern Manitoba. This rock sequence thins toward the east and

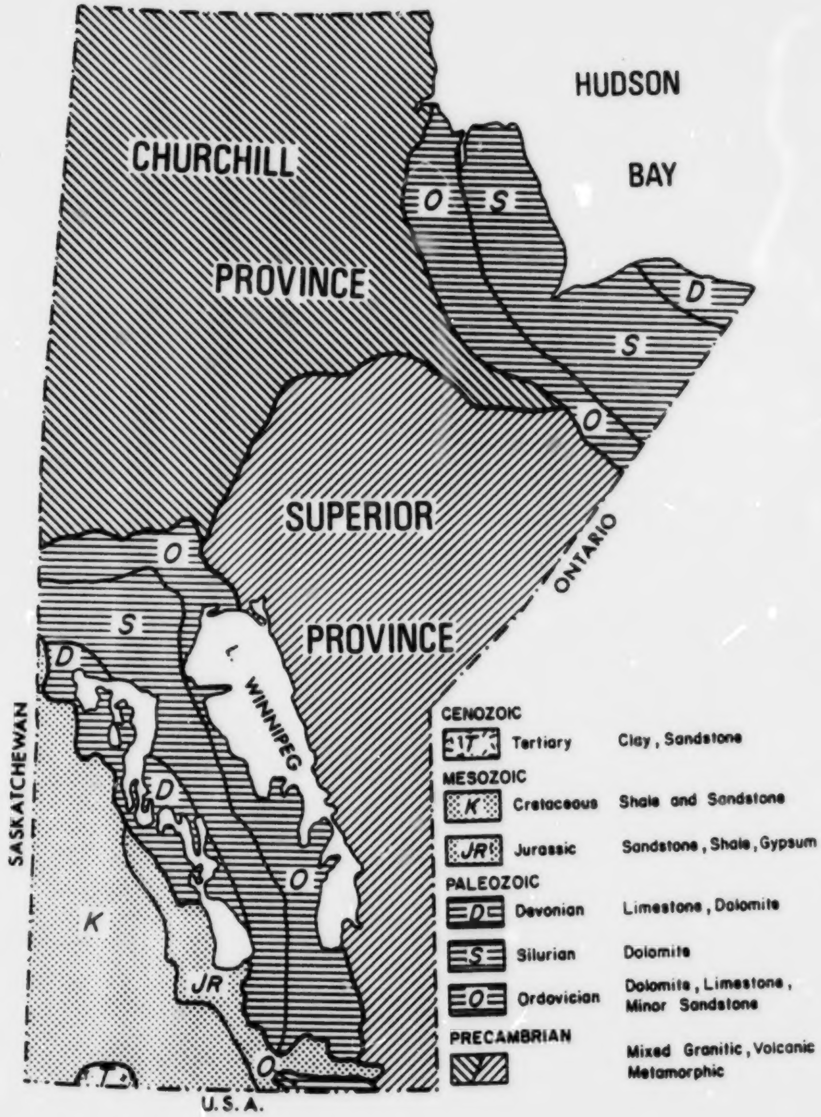

HUDSON
BAY
CHURCHILL
PROVINCE
SUPERIOR
PROVINCE
ONTARIO
SASKATCHEWAN
U.S.A.
L. WINNIPEG
O
S
D
K
JR
T
CENOZOIC
T Tertiary Clay, Sandstone
MESOZOIC
K Cretaceous Shale and Sandstone
JR Jurassic Sandstone, Shale, Gypsum
PALEOZOIC
D Devonian Limestone, Dolomite
S Silurian Dolomite
O Ordovician Dolomite, Limestone, Minor Sandstone
PRECAMBRIAN
Mixed Granitic, Volcanic Metamorphic

Figure 3. Bedrock geology of Manitoba.

thickens westward. An outlier of Tertiary shale, sandstone and lignite overlies Mesozoic rock in the southwest.

Glaciation

During the Pleistocene Epoch, continental glaciers spread across Manitoba and most of Canada on numerous occasions. Repeated glaciation over the past two million years has profoundly influenced Manitoba's topography. Evidence suggests several major periods of glaciation, each lasting thousands of years. The most recent glaciation called the Wisconinan, moved across southern Manitoba about 23 000 years ago, removing most of the pre-existing loose rock and soil and grinding away at the underlying bedrock (Figure 4). As the ice moved southward, some of the debris (till) that had been picked up was plastered down beneath the moving ice but most was not deposited until after the ice began to melt about 16 000 years ago (Teller, 1984).

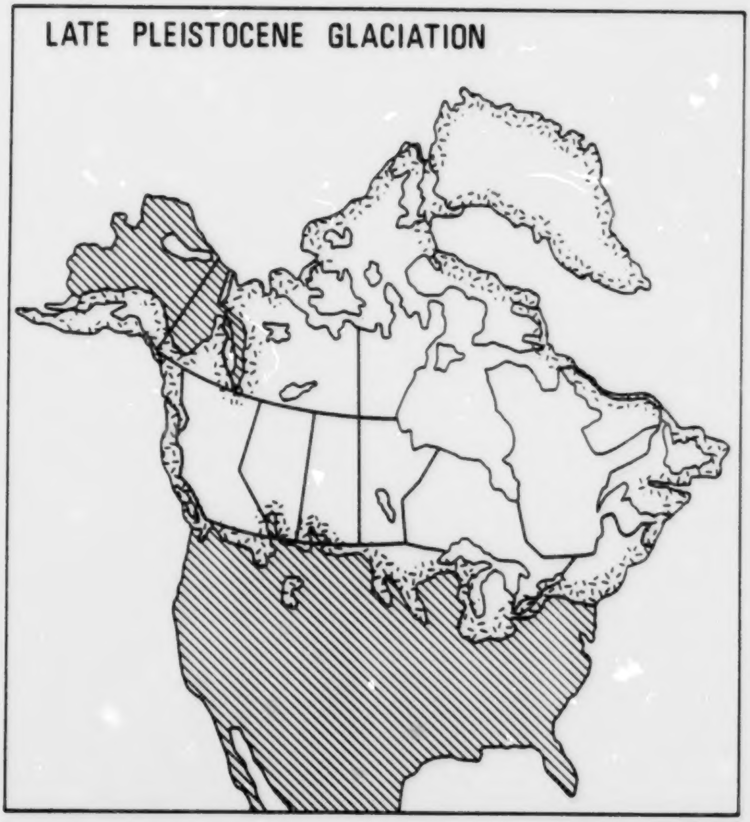


Figure 4. Maximum extent of ice cover during Wisconsinan glaciation (after Prest, 1970).

Another major influence of the glacier was to dam northflowing drainage resulting in formation of a large glacial lake in the low areas in front of the ice. This lake named Lake Agassiz covered parts of southern, central and northern Manitoba from about 11,500 years ago until about 7,500 years ago when the waters were able to drain into Hudson Bay. During this period the lake gradually advanced northward over the province as the edge of the glacier melted back (Figure 5). Extensive areas of lacustrine deposition occurred throughout the Lake Agassiz basin and as the water level dropped, former shoreline features were left high and dry.

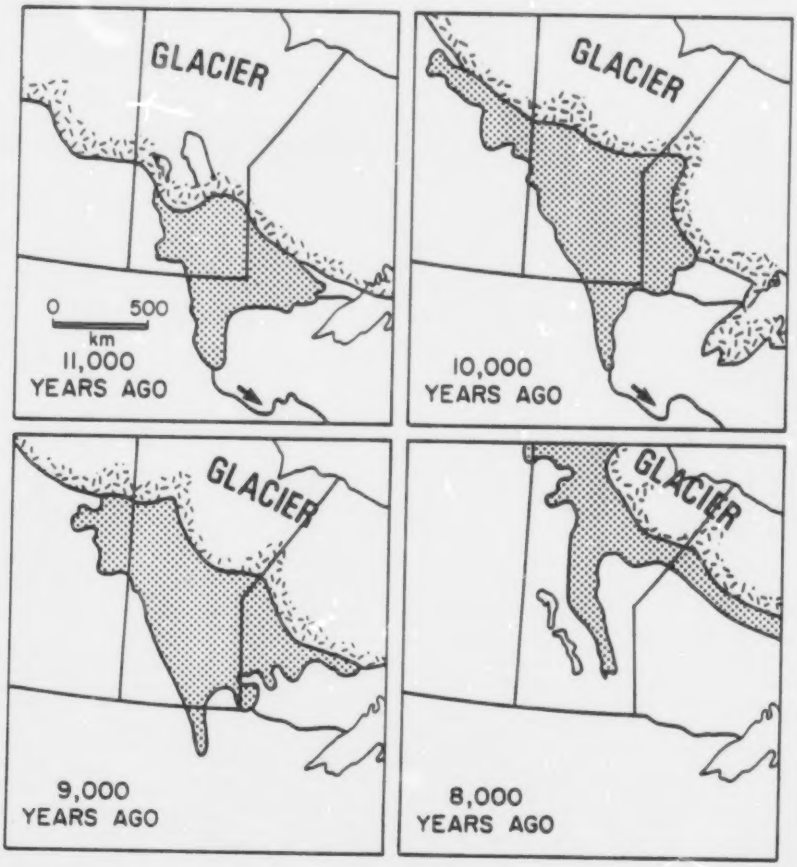


Figure 5. Ice marginal positions and extent of Lake Agassiz at four stages of deglaciation.

The area of Manitoba surrounding Hudson Bay was covered with the thickest portions of the glacier for a much longer period than areas to the south. The great weight of the glacier depressed the earth's crust to the extent that when the ice finally melted the waters of Hudson Bay extended inland for distances of 100 to 200 kilometers.

With the final disappearance of the ice sheet in the Northwest Territories the last glaciation was over leaving the Manitoba landscape to undergo a number of changes. Drainage in the new landscape became entrenched and on other areas floodplains formed. Changing climate caused dry periods which enhanced wind and water erosion. Cold temperatures affected the newly exposed land surface by causing development of permafrost features. During the post glacial period extensive areas of organic terrain developed in poorly drained landscapes. Deposition of alluvial deposits occurred in flood plains and river valleys and continues to the present at many locations.

Surficial Geology

Manitoba's landscape currently bears the legacy of these late Pleistocene glaciations which eroded and reshaped the land surface. Surficial materials in Manitoba can be classified into seven major kinds according to their mode of origin: morainal, lacustrine fluvial, aeolian, alluvial, marine and organic.

Morainal or glacial till deposits originate from glacier ice movement and consist of non-stratified, well compacted material containing a heterogenous mixture of particle sizes. Glacial till is the most extensive surface deposit in Manitoba, occurring as moderately calcareous, loamy, moderately stony to near stone-free material in southwestern Manitoba, as highly calcareous loamy very stony material in areas underlain by limestone and sandy, acidic, excessively stony material in the Precambrian Shield. The till in southwestern Manitoba is derived from a mixture of shale, limestone and granitic rock materials. Hightly calcareous till is derived dominantly from groundup limestone although varying proportions of granitic materials are included. Acidic till in the Shield landscape is derived from granitic and volcanic bedrock.

Lacustrine sediments are the next most common mineral surface deposit in Manitoba. They consist of either stratified fine sand, silt and clay deposited in quiet deep waters on lake beds or moderately well sorted and stratified sand and coarser materials such as beach and near-shore sediments transported and deposited by wave action. Major areas of lacustrine deposition occurred in Lake Agassiz. These silt and clay materials are thick (in excess of 15 m) and continuous in the south but thinner and discontinuous in areas of the north. Sandy and loamy sediments were laid down in smaller glacial lakes in the southwest and local areas of clay sediments were deposited in glacial lakes in contact with disintegrating ice on upland areas in western Manitoba.

Fluvial materials deposited as outwash by fast-flowing water in streams and rivers are generally stratified and moderately well sorted. They consist mainly of rounded gravels mixed with sand and sometimes with minor amounts of silt. Such deposits occur usually at the upper portion of major deltas and within large meltwater channels. Fluvial materials deposited in contact with, on top of, under or adjacent to glaciers are termed ice-contact deposits. Such materials are characterized by a wide range in particle size and usually have surface landforms typical of eskers, kames and kettles. These deposits are most common in portions of northern Manitoba not affected by glacial Lake Agassiz.

Aeolian materials usually consist of well sorted poorly compacted, medium to fine sand and coarse silt. The characteristic duned topography associated with these materials results from modification of sandy and silty lacustrine materials by wind action.

Recent alluvial sediments are generally variably stratified sand, silt and clay layers often interspersed with layers of buried organic matter. These sediments are deposited in flood plains along streams and rivers.

Marine sediments consisting primarily of silt and clay occur in areas around Hudson Bay affected by marine inundation. Sandy and gravelly beach ridges mark the various positions of the marine shoreline as the Earth's crust rebounded enough to cause Hudson Bay to retreat to its present position.

Organic surface materials consist of peat deposits which accumulated in poorly drained portions of the landscape following deglaciation. They form from the remains of mosses, sedges and forest litter and are generally in excess of 60 cm thick but may be up to several meters thick.

A summary of the estimated extent of surface materials, rock and water in Manitoba is shown in Table 2.

Table 2. Estimated extent of surface material in Manitoba.

Soil Parent Material	Area (hectares)	Percent of Province
Morainal	21 505 500	33.2
Fluvial and Aeolian	1 502 550	2.3
Lacustrine	7 245 450	11.2
Recent Alluvium	757 350	1.2
Organic	19 342 800	29.8
Total	50 353 650	77.7
Rock	4 268 700	6.6
Water	10 177 650	15.7
Total	64 800 000	100.0

Source: Ehrlich, W.A. 1962. Surface Deposits and Soils of Northwestern Manitoba. Mimeo Report. 16 pages and map.

PHYSIOGRAPHIC REGIONS AND DIVISIONS

The action of the continental ice sheet on the various bedrock formations in Manitoba has resulted in four main physiographic regions. Within these regions broad patterns of elevation relief and topography form the basis for delineating five major physiographic divisions (Figure 6). Each division has been further subdivided into physiographic sections and subsections recognizing dominant patterns of landforms and associated surficial deposits (Canada-Manitoba Soil Survey, In Prep.). A brief description of the major physiographic regions and divisions recognized in Manitoba follow.

1. HUDSON REGION

Paleozoic rocks blanket this broad depressional area on the surface of the Shield resulting in an extensive flat-lying area of extremely low relief. Present-day Hudson Bay occupies the central depressional portion of the Region, which is still rising due to glacial rebound. Major elements of relief are the valleys of the Churchill and Nelson Rivers incised 18-50 m deep and a series of low beach ridges parallelling the Hudson Bay shoreline. The Hudson Bay Lowland is the only division of the Hudson Region occurring in Manitoba.

A. Hudson Bay Lowland is a flat-lying plain of extremely low relief with elevation ranging from sea level along the Hudson Bay shoreline to 150 m in the west. A series of raised beaches provide local relief in the coastal area bordering the Bay. The underlying Paleozoic bedrock is blanketed by calcareous till which in turn is overlain by marine silts and clays. The surface of the Lowland is dominated by very poorly drained organic terrain characterized by numerous small shallow lakes and ponds. Drainage is poorly developed and local relief occurs mainly in the entrenched valleys of the Churchill and Nelson Rivers.

The South Coast Lowland Section of the Hudson Bay Lowland is divided into two subsections recognizing the local distribution of landforms and surface deposits.

2. KAZAN REGION

The Kazan Region is the physiographic equivalent of the Churchill structural province of the Shield. Much of the region is characterized by broad sloping uplands and plateaux the topography of which reflects the structure and folding of the bedrock in an easterly and northeasterly trend. Relief typically is from 5 to 30 m but ranges from only a metre or two where lacustrine sediment is thick such as just north of Lake Winnipeg (Teller and Bluemle, 1983). The Kazan Upland is the only division of the Kazan Region occurring in Manitoba.

B. Kazan Upland is a rolling to hummocky lake spattered terrain typical of the Precambrian Shield. The upland slopes

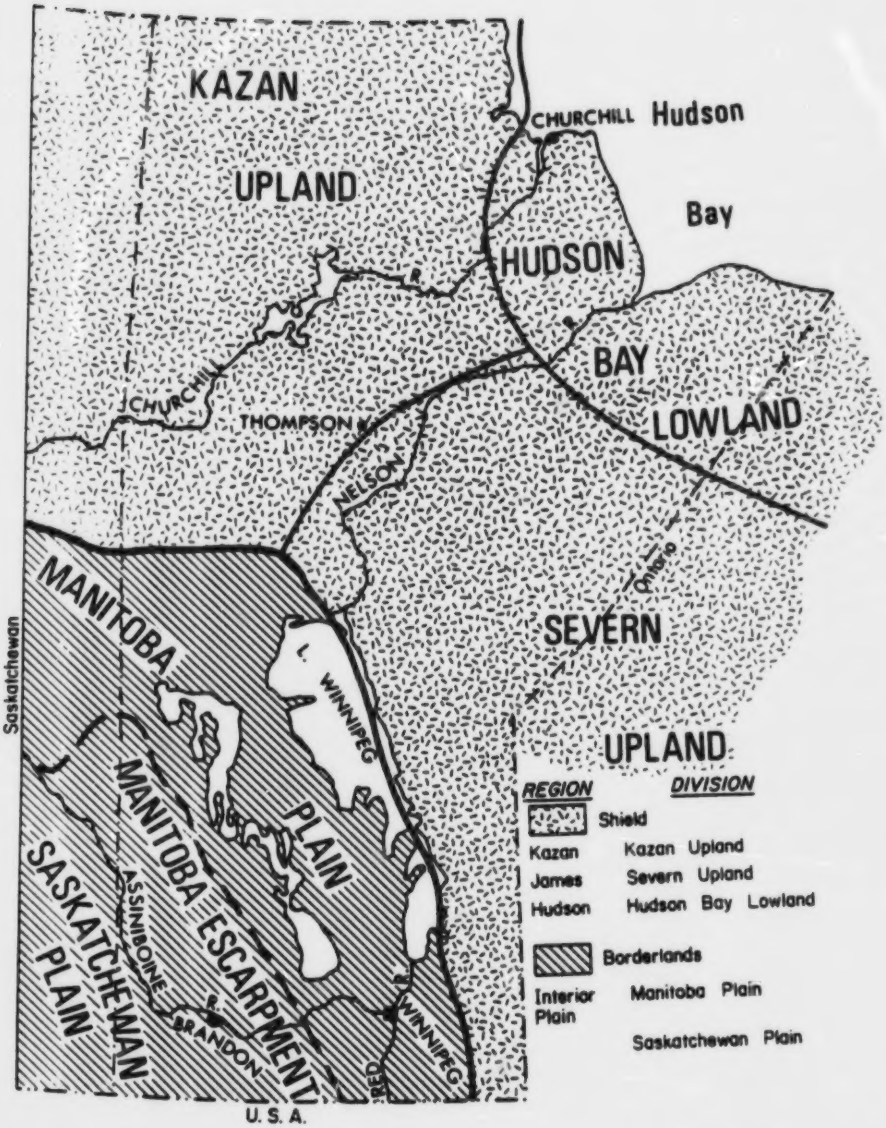

KAZAN
UPLAND
CHURCHILL
Hudson
Bay
HUDSON
BAY
LOWLAND
R.
CHURCHILL
THOMPSON
NELSON
Ontario
SEVERN
UPLAND
Saskatchewan
MANITOBA
PLAIN
L.
WINNIPEG
MANITOBA
ESCARPMENT
SASKATCHEWAN
PLAIN
ASSINIBOINE
R.
BRANDON
RED
R.
WINNIPEG
U. S. A.
REGION
DIVISION
Shield
Kazan
Kazan Upland
James
Severn Upland
Hudson
Hudson Bay Lowland
Borderlands
Interior Plain
Manitoba Plain
Saskatchewan Plain

Figure 6. Physiographic regions and divisions of Manitoba.

gently eastward from 510 m a.s.l. along the Manitoba Saskatchewan boundary to sea level along the Hudson Bay coast. The upland was covered by post-glacial marine overlap reaching as much as 160 km inland and up to 200 m above present sea level. This area forms a coastal plain of little relief mantled largely by reworked drift deposits that obscure nearly all the bedrock (Bostock, 1970; Lee, 1959). Precambrian rock outcrops west of the coastal plain in areas where the glacial and glaciolacustrine deposits are thin and discontinuous. Glaciofluvial ridges are common in the northern area and numerous small and large lakes occur throughout the region.

The Kazan Upland is divided into four physiographic sections and nine subsections recognizing regional landforms and distribution of surficial deposits.

3. JAMES REGION

The James Region is the physiographic equivalent of the Superior structural province of the Shield. The greater part of this region exhibits similar characteristics that are apparent in the Kazan Region. Bedrock trends in this portion of the Shield are reflected in a general allignment of larger lakes and drainageways to the southwest. Relief typically varies from 5 to 30 m but ranges from only a meter or two where lacustrine sediment and peat is thicker and more continuous along the eastern shore of Lake Winnipeg. The Severn Upland is the only division of the James Region in Manitoba.

C. Severn Upland is physiographically similar to the Kazan Upland ranging in elevation from 400 m a.s.l. along the Manitoba-Ontario border to about 150 m a.s.l. along the Hudson Bay Lowland. The hummocky to rolling upland slopes to the west toward Lake Winnipeg and to the north where the Precambrian rock surface dips below the Paleozoic rock of the Hudson Bay Lowland. Much of the terrain is hummocky with extensive rock outcrop and intervening depressions occupied by numerous small and large lakes and pockets of poorly drained organic terrain. The bedrock of the upland is covered with a variable thickness of glacial, glaciofluvial and glaciolacustrine deposits. Level very poorly drained organic deposits dominate an area east and north of Lake Winnipeg.

The Severn Upland is divided into three physiographic sections and eleven subsections in recognition of the distribution of regional landforms and surficial deposits.

4. INTERIOR PLAINS REGION

Flat-lying Paleozoic, Mesozoic and Cenozoic sedimentary strata underlie the Interior Plains Region which extends from the Shield on the east to the foothills of the Cordilleran Region to the west. The slope of the bedrock surface controls much of the large scale morphology of the Region. The region consists of lowlands, plains and uplands, the topography of which is reflective of the underlying rock formations and the effects of glaciation. Relief is low in the eastern portion between the Shield and the Manitoba Escarpment and up to 100 m on higher uplands. The Interior Plain portion of Manitoba is divided into two divisions, the Manitoba Plain to the east and the Saskatchewan Plain to the west.

D. Manitoba Plain is the flattest part of the province, relief being generally less than 8 m. The land surface gradually rises to the west, increasing in elevation from 214 m a.s.l. along the Shield boundary to 300 m at the toe of the Escarpment. The central portion of the plain is dominated by lakes Winnipeg, Winnipegosis and Manitoba all of which are remnants of Lake Agassiz.

Relief varies from level to depressional south of Lake Winnipeg. Within this area deposits of calcareous till, outwash sands and lacustrine silts and clays are dominant. The western side of the plain is characterized by deltaic sands and silts and a series of coarse textured beaches parallel to the Escarpment.

Central and northern portions of the Manitoba Plain are level to undulating with a gentle ridge and swale pattern oriented mainly northwest to southeast. This area is covered by extremely calcareous till capped in places by finer textured lacustrine sediment associated with extensive deposits of coarse outwash, recent alluvium and peat. The lower east-facing slopes of the Escarpment are characterized by sandy deltas and beach ridges deposited by Lake Agassiz.

Thickness of glacial drift on the Manitoba Plain is variable; the till sheet is generally continuous and several metres deep but bedrock outcrops in places to the north. In the southern portion of the plain up to 30 m of silt and clay overlies the till sheet.

The Manitoba Plain is divided into eight physiographic sections and twenty subsections in recognition of the distribution of landforms and surficial deposits.

E Saskatchewan Plain is underlain by gently dipping Mesozoic sedimentary rock strata covered by extensive undulating to hummocky drift deposits. The eastern edge of the plain is clearly marked by the Manitoba Escarpment formed in part by underlying strata of Cretaceous shale rock. One of the main reasons for the high elevation of the Escarpment is the presence of the resistant uppermost shale which has protected the softer shales beneath from erosion. The Escarpment has however been dissected by the Pembina, Assiniboine, Valley, Swan, Red Deer and Saskatchewan rivers which have cut through the Escarpment leaving an irregular series of hilly uplands.

Local relief west of the Escarpment where the surface is composed of a mix of glacial, glaciofluvial and glaciolacustrine sediment is as much as 100 m on upland tracts and more than that near major river valleys. The till cover is dominantly a mixture of Precambrian granite, Paleozoic limestone and Cretaceous shales of local origin. The thickness of the glacial drift varies from a few metres to more than 200 m on the higher uplands. Local areas of shaly till are commonly thin and occur directly on shale bedrock. Glaciolacustrine sediments occur as thin discontinuous veneers or thicker blankets overlying till. Deltaic deposits are as much as 200 m thick within the old Assiniboine delta.

The Saskatchewan Plain portion of Manitoba is divided into eleven physiographic sections and nineteen subsections recognizing the distribution of regional landforms and surficial deposits.

PHYSIOGRAPHIC SECTIONS AND SUBSECTIONS

The physiographic description of Manitoba at the regional level is in terms of 27 sections mapped at a scale of 1:2 000 000. Section descriptions are generalized from the more detailed characterization provided for subsections. The section descriptions provide an overview of the physiography of Manitoba and serve to introduce, organize and correlate the more detailed subsection description.

Physiographic description of subsection delineations on the Physiographic Map of Manitoba have been compiled in an Extended Legend. This legend provides a summary of the physiographic characteristics for each subsection in terms of elevation, topography and landform, surface deposits, bedrock geology and drainage. An example of the content of portions of the extended legend is shown in Table 3.

GUIDE TO UNDERSTANDING THE EXTENDED LEGEND

1. Map Units

Each subsection is identified by name and an alphanumeric code to show its relationship to the physiographic section and major physiographic regions and divisions.

2. Elevation

The general range in elevation is given for each subsection in meters above mean sea level (m a.s.l.).

3. Topography and Landform

Each subsection is described in terms of dominant topographic expression amd genetic landform type. Co-dominant combinations of significant topography and landforms or minor inclusions of sharply contrasting landforms are described.

Descriptive terminology is according to the Landform Classification developed for use by soil surveys in Canada (Agriculture Canada Expert Committee on Soil Survey, 1987). Surface expression criteria are applied to mineral and organic

Table 3. Portion of extended legend description of physiographic subsections of Manitoba.

PHYSIOGRAPHIC DIVISIONS OF MANITOBA
EXTENDED LEGEND

Physiographic Subsection	Elevation m. a.s.l.	Topography and Landform	Surface Deposits	Bedrock Geology	Drainage
			A HUDSON BAY LOWLAND DIVISION A1 SOUTH COAST LOWLAND		
A1.1 Coastal Lowland	0-75	Level to depressional marine plain broken by numerous subdued beach ridges; extensive tidal flats.	Extensive shallow mesic fen organic deposits underlain by silty marine sediments. Local areas of moderately calcareous sandy beach deposits. Calcareous silty marine sediments and brackish marshes occur along Hudson Bay shoreline.	Silurian dolomites, dolomitic limestone and limestone, minor Devonian limestones.	Numerous very small lakes and undrained depressions; uniform medium density parallel network of secondary drainage ways flowing into Hudson Bay.
A1.2 Owl-Kaskattama Lowland	0-150	Level to depressional marine veneers and blankets; local areas of undulating and fluted moraine, locally prominent marine beach ridges.	Extensive deep mesic forest and fen organic deposits underlain by silty marine sediments, local areas of very strongly calcareous loamy waterworked till and moderately calcareous sandy beach deposits; minor occurrence of loamy alluvium in major river valleys.	Silurian dolomites, limestone and dolomitic limestone; Ordovician dolomites and limestones.	Numerous very small lakes and undrained ponds; four primary rivers traverse the area; local drainage provided by a uniform medium density network of secondary streams with dendritic pattern.
			B KAZAN UPLAND B1 GRASS-BURNTWOOD RIVER PLAIN		
B1.1 Snow Lake Plain*	255-375	Hummocky to undulating morainal veneers and lacustrine blankets, steeply sloping irregular bedrock ridges and knolls commonly occur above 275 m elevation.	Widespread occurrence of acidic sandy stony till of granitic origin in association with extensive rock outcrops; locally extensive moderately calcareous clayey lacustrine sediments overlain in depressional areas by mesic forest peat and local areas of fibric Sphagnum and mesic fen peat.	Precambrian tonalite-granodiorite, granites and gneiss, local volcanics.	Numerous very small and few small to medium size lakes. Uniform medium density dendritic and irregular bedrock controlled network of secondary streams flowing general north and northeasterly.
B1.2 Three Point Lake Plain	255-330	Undulating to hummocky lacustrine blankets and locally extensive bedrock ridges and knolls.	Moderately calcareous clayey lacustrine sediments, overlain in depressions by mesic forest peat and local areas of fibric Sphagnum and mesic fen peat. Minor areas of rock outcrop are associated with pockets of acidic sandy till of granitic origin.	Precambrian gneiss and schist with granites and granodiorite.	Few small and very small lakes; uniform, low density deranged (dendritic) pattern of secondary streams flowing generally north to northeast.

genetic landform classes and bedrock classes.

4. Surface Deposits

The dominant surficial materials within each subsection are described according to criteria used by the cooperative soil survey in Canada (Agriculture Canada Expert Committee on Soil Survey, 1987) and defined in the Manual for Describing Soils in the Field (ECSS, 1982). The criteria used describe chemical composition, lithology, texture and stoniness of the deposits.

5. Bedrock Geology

The dominant bedrock conditions underlying, or found at the surface of each subsection are summarized from the bedrock descriptions for the Geological Map of Manitoba, (Manitoba Mineral Resources Division, 1979).

6. Drainage

The surface water and dominant drainage characteristics are described for each subsection.

Lakes: Descriptive terminology modified from Welch (1978) in terms of amount of water bodies relative to size of map unit and size of water bodies ranging from very small to very large (<38 km^2 to >1152 km^2).

Drainageways: Descriptive terminology is adopted from Lueder (1959) in terms of uniformity or homogeneity of pattern within the landscape, density or number of drainageways per unit area of land surface, orientation or direction of drainage, degree of control exerted by bedrock or glaciation on orientation and pattern of surface drainage. Drainageways are also described according to size and order of drainage and whether they are permanent or intermittent.

SUMMARY

The physiographic description of Manitoba at a 1:2 000 000 scale is provided in terms of four Regions and five Divisions divided into twenty-seven physiographic sections and sixty-one Subsections. Physiographic attributes are described in narrative form to the section level and by means of an extended legend at the subsection level.

Development of the physiographic map has evolved with the progression of the systematic soil survey of Manitoba. The distribution of surface deposits in relation to underlying bedrock and the glacial history of the province are major causative factors affecting the occurrence and distribution of soil properties. For this reason, understanding physiographic relationships is important for correlation of the soil mapping program in the province. The physiographic map also provides a convenient means of stratifying and organizing soil data for land evaluation and analyses. Soil properties can be linked to other land and water data compiled on a large area basis such as major physiographic units and watersheds.

The physiographic map of Manitoba provides a readily recognizable organization of landscapes at a broad scale. This organization of land attributes will be of use to those responsible for planning land use and management as well as others concerned with environmental quality at the broad regional and provincial level. In addition, substantial education value concerning the nature of Manitoba landscapes can be derived from the physiographic map.

REFERENCES

Acton, D.F., Clayton, J.S., Ellis J.G., Christiansen, E.A. and Kupsch, W.O., 1960. Physiographic Divisions of Saskatchewan.

Agriculture Canada Expert Committee on Soil Survey. 1987. The Canadian System of Soil Classification. 2nd Ed. Agric. Can. Publ. 1646. 164pp.

Alcock, F.J. 1918. Wekusko Lake area northern Manitoba; Geological Survey of Canada, Summary Report. 1917. Part D. p. 8-17.

Bostock, H.S., 1969. Physiographic regions of Canada; Geological Survey of Canada, Map 1254A.

Bostock, H.S., 1970. Physiographic subdivisions of Canada; Geological Survey of Canada, Economic Geology Report No. 1, p. 10-32.

Canada-Manitoba Soil Survey. 1940-1985. All published reconnaissance Soil Survey Reports and Maps. Office of the Queen's Printer Statutory Publications. Winnipeg, Manitoba.

Canada Manitoba Soil Survey. 1976-1979. Published Biophysical Surveys of Northern Manitoba. Surveys and Mapping Branch, Manitoba Department of Natural Resources.

Canada-Manitoba Soil Survey, in Prep. Physiographic Subdivisions of Manitoba. Report, descriptive legend and map, scale 1:2 000 000.

Davies, J.F., Bannatyne, B.B., Barry, G.S., and McCabe, H.R., 1962. Geology and mineral resources of Manitoba. Manitoba Department of Mines and Natural Resources.

Dredge, L.A., Nixon, F.M. and Richardson, R.J., 1986. Quaternary geology and geomorphology of northwestern Manitoba. Geological Survey of Canada. Memoir 418. 38 pp.

ECSS, 1982.Expert Committee on Soil Survey. The Canada Soil Information System (CanSIS). Manual for describing soils in the field. 1982. revised. LRRI Contribution No. 82-52 Research Branch, Agriculture Canada, Ottawa, Ontario.

Klassen, R.W., 1966. Surficial geology of the Waterhen-Grand Rapids Area, Manitoba. 63B, 63G. Geological Survey of Canada. Paper 66-36. 6p.

Klassen, R.W., 1979. Pleistocene geology and geomorphology of the Riding Mountain and Duck Mountain Areas, Manitoba-Saskatchewan. Geological Survey of Canada, Memoir 396. 52pp.

Klassen, R.W., 1986. Surficial geology of north-central Manitoba; Geological Survey of Canada. Memoir 419. 57pp.

Lee, H.A., 1959. Surficial geology of southern District of Keewatin N.W.T., Geol. Surv. Can. Bull. 51, 42pp.

Lueder, Donald R., 1959. Aerial Photographic Interpretation, Principles and Applications. McGraw-Hill Book Co. Inc., New York. 462 pp.

Manitoba Mineral Resources Division, 1979. Geological Map of Manitoba Scale 1:1 000 000 Map 79-2.

Manitoba Mineral Resources Division, 1981. Surficial Geological Map of Manitoba. Scale 1:1 000 000. Map 81-1.

Prest, V., 1970. Quaternary Geology of Canada: in Douglas, R. (editor), Geology and Economic Minerals of Canada: Geological Survey of Canada, Economic Geology Report 1, p. 675-764.

Teller, James T. and Bluemle, John P., 1983. Geological setting of the Lake Agassiz basin: in Teller J.T. and Clayton, Lee. eds. Glacial Lake Agassiz: Geological Association of Canada Special Paper 26.

Teller, J.T., 1984. The Ice Age and its Legacy. Chapter 2 pp.23-47: in Teller, J.T. ed. Natural Heritage of Manitoba -Legacy of the Ice Age. Manitoba Museum of Man and Nature.

AGROECOLOGICAL RESOURCE AREAS OF SOUTHERN MANITOBA

by

R.G. Eilers and G.F.Mills
Canada-Manitoba Soil Survey

ABSTRACT

A Map of the Agroecological Resource Areas of Southern Manitoba has been developed to provide a natural resource based framework for provincial and regional agricultural land evaluations. It was derived from the generalized map of Soil Landscapes of Manitoba (LRRC, 1989), Eco-climatic Regions (Mills et al. 1985), and the Agricultural Resource Regions Map of Southern Manitoba (Faculty of Agriculture, 1974). The grouping of landscapes was based on broad units of land which had general similarities of agricultural potential, land use and management. Each of the areas was defined on the basis of climate, soils, texture and landform. The various combinations of these components have a major impact on the type and diversity of agriculture. Agroecological Resource Areas of generally similar agricultural potential and management were grouped into Regions defined on the basis of eco-climatic zones, physiographic subdivisions and dominant soil characteristics. The Agroecological Resource Area Map of Southern Manitoba portrays 50 different areas within 10 separate regions.

A computerized extended legend contains additional information about the types of soil, landuse and management. Some general agro-climatic parameters such as frost free days, length of growing season, growing degree days, and seasonal and annual precipitation are also provided. This Agroecological map is currently being used as the base for the Manitoba portion of the Prairie Region Land Evaluation (PRLE) project of Agriculture Canada's Land Resource Research Centre. Analysis and evaluation of Manitoba's agricultural land resource is accomplished within the biophysical framework provided by this map. In addition, as a result of the PRLE project, links have been built to other data bases such as Statistics Canada.

INTRODUCTION

Over the last number of years, the major focus of the soil survey program in Manitoba has been on large scale mapping of small project areas to meet specific resource information needs. At the same time, however, a growing need has developed to have small scale, resource based maps of the province as a whole, for assessing the extent, quality, use and productive potential of our soil resources for sustained agricultural landuse. The first attempt to provide this kind of base map was the Land Resource Regions map published by the Faculty of Agriculture in 1974. This map was patterned after the concept of Land Resource Regions as described and utilized in the United States (Austin, 1965). The objective of the US map was to provide a practical base for general applications related to farming, ranching, forestry, engineering, recreation and other uses. The broad concept of Land Resource Regions in the US was based on the dominant physical characteristics of landuse, elevation and topography, climate, water, and soil. The application of these components was modified somewhat for Manitoba conditions to accomodate a smaller scale differentiation of more subtle differences in soils, climate, landuse and physiography in Agro-Manitoba.

In the mid 1980's, in response to the need for standardized soil resource data at a uniform level of detail, a more comprehensive project was undertaken to develop and compile a map of Generalized Soil Landscapes (GSL) for all of Manitoba (Canada Soil Inventory, LRRC 1989). This GSL map was compiled at a scale of 1:1 M, largely from data derived from available reconnaissance and exploratory soil surveys. The standardized map and legend for the soil landscapes shown on the GSL is designed to meet provincial and regional needs for landuse planning and management and has been used as a base for mapping and describing the general risks of wind and water erosion and soil salinization.

The first objective of this paper is to describe the development of a map and data base characterizing the Agroecological Resource Areas (ARA) of Southern Manitoba. The combination of physiographic, ecologic and climatic data provides a biophysical framework capable of relating agricultural landuse and productive potential to a physical assessment of the soil resources of the province. A second objective is to illustrate, the use of this framework (derived maps) in the rationalization, direction, and targeting of research, conservation, extension and planning at a regional and provincial scale.

METHOD

The ARA map for southern Manitoba was developed through a series of overlay procedures utilizing the Land Resource Regions and Areas map of Southern Manitoba (Faculty of Agriculture, 1974), the Ecoclimate Regions map of Manitoba (Mills et al. 1985) and the Generalized Soil Landscapes (GSL) map of Manitoba (Canada Soil Inventory, LRRC 1989). In the first phase, the GSL map for Manitoba was reduced to 1:2 M scale and used as the base map. The Land Resource Regions map (1974) was then adjusted to 1:2 M scale and overlaid on the GSL map. The objective was to delineate ARA polygons which were relatively homogenous in terms of climate, texture, soil development and landform. Each ARA polygon was delineated by using the nearest soil landscape boundary from the base map. This resulted in an aggregation of GSL map polygons into 50 ARA polygons at 1:2 M scale for Agro-Manitoba.

In the second phase, the Ecoclimatic Regions map was overlaid on the 1:2 M scale base map and the nearest appropriate GSL polygon boundary was again utilized to delineate the Agroecological Resource Regions (ARR) of Agro-Manitoba. This process resulted in an aggregation of the 50 ARA units into 10 broad units which essentially constitute the biophysical framework of southern Manitoba. Through the use of this overlay technique it has been possible to maintain these maps in a hierarchial system such that an easy correlation can be made between the various polygons on each map. This correlation facilitates access to data in the extended legend for the GSL map for further generalization and use with the ARA map. Some map users however, may note minor differences in the boundaries of generalized maps derived from this ARA base when compared to original source maps. This is due to the overlay process which selected the most appropriate GSL polygon boundaries for generalization to the 1:2M base used for compiling the ARA map.

The criteria used to distinguish each area were based on the general dominance or consistent mixes of differentiating characteristics of agro-climate, landform, soil texture, and soil development. Polygons were delineated on the basis of eco-climatic zones, physiography and major soil conditions. For example, prairie was separated from parkland and forest, hilly uplands from undulating plains, sands from clays, and Chernozemic soils from Organic and Luvisolic soils.

ARA map polygons have been numbered consecutively from 1 to 50 with numbers 1 to 20 occurring in the western uplands portion of Agro-Man and numbers 21 to 50 in the central and eastern lowlands area. The smallest ARA polygon covers an area of approximately 3.8 townships (36.1 Kha) and the largest ARA polygon includes approximately 98.7 townships (920.8 Kha). This range in size of polygons allows for linkages to other data sources which may be at an even more generalized level.

The ARA map for southern Manitoba depicts broad areas of generally similar agricultural potential, landuse and management (Figure 1). The extent of the ARA map area is essentially the area covered by reconnaissance soil surveys in southern Manitoba. The eastern and northern limits of this map are coincident with the boundary defined by the Canada Land Inventory (CLI 1970).
The map covers an area of approximately 14,687 Kha and includes all of the land currently used for agriculture as well as some of the potential agricultural land in the northern Interlake and WestLake areas.

DEFINITIONS

Agroecological Resource Region (ARR): the broadest grouping, is a large area with broad similarity in agriculture potential and kinds of farming. It is separated on the basis of general agro-climatic and physiographic characteristics.

Agroecological Resource Area (ARA): a subdivision of ARR, is a natural landscape area that is more or less uniform in terms of agro-climate, landform, soils and general agricultural potential.

MAP LEGEND CRITERIA

The differentiating criteria for a map at this scale consist of four major components; landform, texture, soil development and general agricultural climate. The definition of each component as used on this map is as follows:

Landform: this resource characteristic reflects broad slope and shape features. Three categories are recognized in Manitoba: undulating and level plains with slopes of < 5 % **(P)**; hummocky uplands or hill lands with slopes of 5 - 15 % **(H)**; and steeplands with slopes > 15 % **(S)**.

Texture: five general categories of particle size (Family level, ECSS 1987) were recognized based on an average of the surface and subsoil characteristics. These were: sandy **(S)**, coarse loamy **(COL)**, fine loamy **(FML)**, clay **(C)**, and organic **(O)**. Although not a texture, rock **(R)** was designated in those ARA's where bedrock was a significant surface condition.

Soil Development: general categories were recognized to the Order or Great Group level in taxonomy (ECSS, 1987). These were Chernozemic Black (**BL**) and Dark Gray (**DG**); Luvisolic - Gray (**GL**); Gleysolic - Rego (**G**); Regosol - Orthic (**RO**) and Cumulic (**RC**); Brunisol - Dystric (**BD**) and Eutric (**BE**); and Organic (**O**).

Agro-climate: a very general designation based on heat limitations as proposed by the current national Working Group on Agri-cultural Capability Classification, was used to describe this component. The four classes recognized in Manitoba are: no significant heat limitations (**1**); slight heat limitations (**2H**); moderate heat limitations (**3H**); and severe heat limitations (**4H**).

COMPUTERIZED EXTENDED LEGEND

The extended legend for the ARA map is presented in a typical spread sheet fashion using a "d Base" file structure. The legend has been organized into 4 general sections as illustrated schematically in Table 1. The number and type of attributes currently contained in each of these sections is listed in Table 2. These files may be updated from time to time as new information becomes available. The current data in the extended legend was obtained from the previously mentioned map references as well as from Dunlop, 1981 and Environment Canada, 1980.

TABLE 1. Schematic Format of Computerized Extended Legend For ARA Map

<table>
<tr><th></th><th colspan="8">SECTIONS</th></tr>
<tr><th></th><th colspan="2">A</th><th colspan="2">B</th><th colspan="2">C</th><th colspan="2">D</th></tr>
<tr><th>POLYGON NO.</th><th colspan="8">ATTRIBUTES</th></tr>
<tr><td></td><td>|x|</td><td>|o|</td><td>|=|</td><td>|+|</td><td>|&|</td><td>|$|</td><td>|*|</td><td>|#|</td></tr>
<tr><td></td><td>|x|</td><td>|o|</td><td>|=|</td><td>|+|</td><td>|&|</td><td>|$|</td><td>|*|</td><td>|#|</td></tr>
<tr><td>1.</td><td>x</td><td>o</td><td>=</td><td>+</td><td>&</td><td>$</td><td>*</td><td>#</td></tr>
<tr><td>2.</td><td>x</td><td>o</td><td>=</td><td>+</td><td>&</td><td>$</td><td>*</td><td>#</td></tr>
<tr><td>3.</td><td>x</td><td>o</td><td>=</td><td>+</td><td>&</td><td>$</td><td>*</td><td>#</td></tr>
<tr><td>.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>49.</td><td>x</td><td>o</td><td>=</td><td>+</td><td>&</td><td>$</td><td>*</td><td>#</td></tr>
<tr><td>50.</td><td>x</td><td>o</td><td>=</td><td>+</td><td>&</td><td>$</td><td>*</td><td>#</td></tr>
</table>

Section	Description	No. of Attributes
A	Soils and Terrain	17
B	Capability and Land Use	11
C	Temperature related	9
D	Precipitation related	10

TABLE 2. Description of Attributes in Extended Legend For ARA Map

Section A. Soils and Terrain

-Polygon number
-Agroecological Resource Area Name
-Landform
-Textural Group
-Soil Great Group
-Ag_climate
-Dominant Parent Material Origin
-Dominant Parent Material Texture
-Dominant Slope Class
-Dominant Slope Length
-Dominant Soil 1 (series symbol)
-Dominant Soil 2 (series symbol)
-Major Agricultural Soil 1 (series symbol)
-GSLM Polygon number reference for Soil 1
-Major Agricultural Soil 2 (series symbol)
-GSLM Polygon number reference for Soil 2
-Major Agricultural Soil 3 (series symbol)
-GSLM Polygon number reference for Soil 3

Section B. Capability and Land Use

-Dominant Soil Drainage
-Subdominant Soil Drainage
-Dominant Soil Problems
-Subdominant Soil Problems
-Dominant Agriculture Capability
-Subdominant Agriculture Capability
-Dominant Land Use
-Subdominant Land Use
-Dominant Ecoclimate
-Estimated Average Elevation of Central Area
-Estimated Variation of Average Elevation

-Location of Centroid of ARA Polygon = Township
-Location of Centroid of ARA Polygon = Range
-Location of Centroid of ARA Polygon = Direction

Section C. Temperature related

-Mean Annual Air Temperature
-Maximum Air Temperature
-Minimum Air Temperature
-Mean Frost Free Period
-Maximun Frost Free Period
-Minimum Frost Free Period
-Mean number of Growing Degree Days
-Maximum number of Growing Degree Days
-Minimum number of Growing Degree Days

Section D. Precipitation related

- -Mean Annual Precipitation
- -Maximum Annual Precipitation
- -Minimum Annual Precipitation
- -Mean Growing Season Precipitation
- -Maximun Growing Season Precipitation
- -Minimum Growing Season Precipitation
- -Equivalent Soil Water Deficit to end August
- -Variation of Equivalent Soil Water Deficit to end August
- -Equivalent Soil Water Deficit to end of September
- -Variation of Equivalent Soil Water Deficit to end September

The climatic data in the extended legend (section C and D) was initially compiled for the Ecoclimatic Regions Map (Mills et et 1985). This compilation was based on approximately 60 weather stations which had sufficient long term data to characterize weather conditions. This weather data has been used to calculate general thermal and moisture parameters important for cropping conditions in southern Manitoba. Specific climatic parameters calculated for each Ecoclimatic Region, have been assigned to each ARA comprising that region. These parameters are included in the computerized extended legend (Sections C and D, Table 2) which will accompany the final published map. A future update is planned for this legend which will generate agronomic weather parameters for each individual ARA utilizing data for those stations that occur within the given ARA polygons. The data for each station will also be utilized to calculate daily weather parameters for each ARA using the Thiessen polygon weighting method. These data will be available on request from the Agrometerology Section of the Land Resource Research Centre in Ottawa.

NAMES OF REGIONS AND AREAS

Names can be useful for quick reference and orientation. This is particularly true if they are connotative or representative, and so, names representative of geographic location and extent were assigned to the various regions and areas on this map. Each of the ARA's were given single names after a major town or geographic place central to the area such as Portage, Winkler, or Dauphin. The ARR's in most cases, were given double names by selecting towns or landmarks to depict the general areal extent of the region (Table 3). For example, the Killarney-Reston Region designates an area in the extreme southwest corner of the province while the Steinbach-Swan River Region defines a zone along the eastern side and interlake areas of Agro-Man.

TABLE 3. Correlation of Agroecological Resource Regions (ARR), Ecoclimatic Regions (ECR), and Agroecological Resource Areas (ARA) for Southern Manitoba.

ARR name	ECR-symbol*	ARA polygon number/name
Killarney-Reston	GT3	1, Souris
		2, Reston
		5, Killarney
Manitou-Russell	GT2	3, Hargrave
		6, Hilton
		7, Manitou
		9, Stockton
		10, Shilo
		11, Carberry
		12, Hamiota
		13, St. Lazare
Winkler-Gladstone	GT4	29, MacGregor
		30, St Claude
		33, Portage
		34, Winkler
Emerson-Dauphin	GT1	17, Grandview
		22, Dauphin
		23, Alonsa
		24, St. Rose
		27, Lundar
		28, McCreary
		31, Gladstone
		32, Langruth
		35, Winnipeg
		36, Emerson
Steinbach-Swan River	LBs1	14, Erickson
		15, Roblin
		19, Kenville
		21, Swan River
		25, Gypsumville
		26, Gimli
		37, Stienbach
		38, Piney
		39, Stead
		41, Grindstone
		43, Waterhen
		44, Ashern
Turtle Mtn-Altamont	LBs2	4, Turtle Mountain
		8, Altamont
Riding-Duck-Porcupine	MBs2	16, Riding Mountain
		18, Duck Mountain
		~~20, Por~~cupine Mountain
The Pas	MBs4	~~45.~~ The Pas
Grindstone-Swan Lake	MBs1	46, Wanless
		47, Overflowing River

		48. Swan Lake
		49. Chitik Lake
		50. Sturgeon Bay
Whitemouth-Bisset	LBst	40. Whitemouth
		42. Bissett
Berens River	MBs3	not classified.

---

* GT = Grassland Transitional, LBs = Low Boreal subhumid, LBst = Low Boreal subhumid transitional, MBs = Mid Boreal subhumid.

LINKAGES AND APPLICATION

One of the major advantages of this ARA map is the linkage of land based data to climatic data relevant to land evaluation for agricultural uses. This linkage will enable users to evaluate the general growing conditions across the province in terms relevant to specific kinds of cropping systems. For example, in determining the suitability of an area for various field crops, length of frost free period, growing season precipitation, and soil textures, are critical factors. Through the use of this map and computer legend, a quick assessment can be made to identify the soil textural group, growing degree-days and growing season precipitation which will indicate the relative risk for bringing specific crops to maturity. Examples of maps derived from this system showing distribution of major textural groups, frost free days and mean growing season precipitation in southern Manitoba are shown in Figures 2, 3, and 4, respectively.

Since this ARA map has been compiled from other existing maps, ready-built linkages have also been maintained through polygon correlation tables. This means that data from other sources such as the extended legend of the GSL map can be easily accessed. Also, since the GSL map units have been rasterized at the 1/4 section level, linkages can also be made to the Manitoba Provincial Soil Testing Laboratory, the Manitoba Crop Insurance Corporation and other socio-economic databases stored on a 1/4 section basis.

The ARA map of southern Manitoba will be useful for many applications. For example, the polygons have been linked to the enumeration areas of Statistics Canada as part of the Prairie Regional Land Evaluation (PRLE) project of Agriculture Canada's Land Resource Research Centre. It will serve as a biophysical landscape framework for the description of farm-level cropping systems in Manitoba (Hiley et al. in prep.). It will also serve as a general framework for improved analysis of crop yields for cereals, oilseeds, and forages utilizing simulation modeling techniques currently under way in LRRC. In addition, it may have application as a natural resource based framework for use by the Manitoba Crop Insurance Corporation's insurance services program. It is also anticipated that this map will serve a valuable educational function in the teaching and utilization of Geographic Information System technology where broad level information is required for general agricultural and other land use planning.

CONCLUSIONS

The Agroecological Resource Areas Map of Southern Manitoba is one in a series of general resource maps which have been developed and correlated for each of the prairie provinces. This map was developed to provide a natural resource framework for the rationalization, direction, and targeting of research, conservation, extension and planning at a regional or provincial scale. The uniqueness of this map lies in its integration of the physical land resource base with elements of agricultural climate. It currently has application to the PRLE project of Agriculture Canada's Land Resource Research Centre.

ACKNOWLEDGEMENTS

The following people have contributed significantly to this paper. R.E. Smith, and W. Fraser for constructive discussion and review; and N. Lindberg for the compilation of data contained in the extended legend.

REFERENCES

CLI 1970. Objectives, scope and organization. Report No. 1. Canada land Inventory, Canada Dept. Regional Economic Expansion, Ottawa. iv + 61 pp. .

Dunlop, S.L. 1981. An Agroclimatology of Southern Manitoba. M. Sc. Thesis, Department of Soil Science, University of Manitoba.

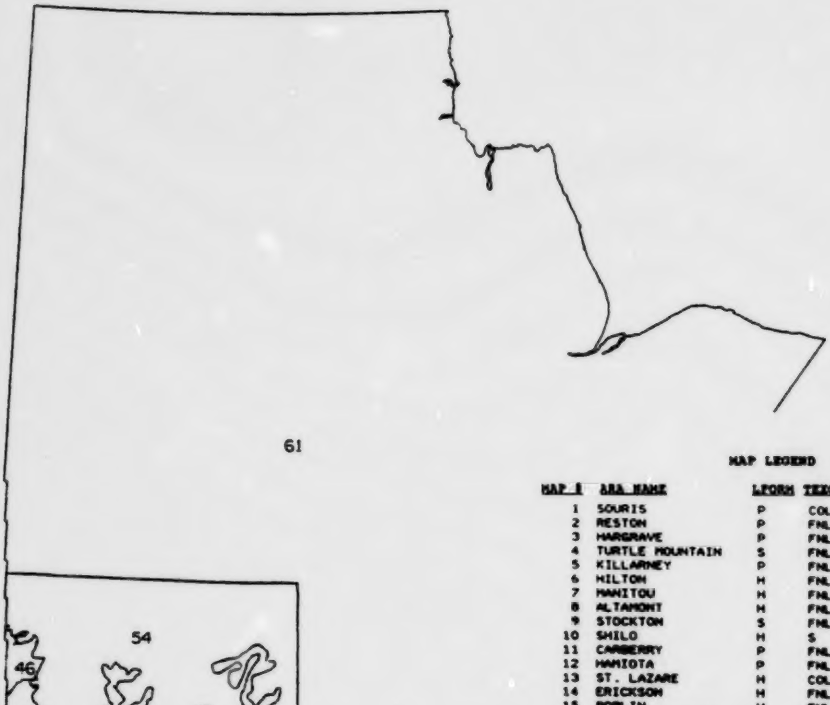
ECSS 1987. Agriculture Canada Expert Committee on Soil Survey. The Canadian system of soil classification. 2nd ed. Agric. Can. Publ. 1646. 164 pp.

Environment Canada, 1980. Canadian Normals 1951-1980,
a) Temperatures, vol. 2, and b) Precipitation, vol. 3,
c) Frost Free Days, vol. 6, and d) Growing Degree-Days, vol. 4.
Atmoshperic Environment Service, Downsview, Ontario.

Faculty of Agriculture 1974. Land Resource Regions and Areas in Southern Manitoba, Chapter 5. SOILS, in Principles and Practices of Commercial Farming, 5th Ed. Pub. by Faculty of Agriculture, University of Manitoba, pp 43-51 .

LRRC (Land Resource Research Centre) 1989 Generalized Soil Landscapes Map, Manitoba. Pub. Research Branch, Agriculture Canada.

Mills, G.F., Veldhuis, H., Stewart, J.M., Wotton, D., and Koonz, W. 1985 Ecoclimatic Regions of Manitoba, prepared for the National Wetlands Working Group.



MAP LEGEND

MAP #	ARA NAME	LFORM	TEXGRP	SOIL GG	AG CLIM
1	SOURIS	P	COL	BL-(G)	2H
2	RESTON	P	FNL	BL	2H
3	HARGRAVE	P	FNL	BL	2H
4	TURTLE MOUNTAIN	S	FNL	DG-(GL)	2H
5	KILLARNEY	P	FNL	BL	2H
6	HILTON	H	FNL	BL-(DG)	2H
7	MANITOU	H	FNL	BL-(DG)	2H
8	ALTAMONT	H	FNL	DG	2H
9	STOCKTON	S	FNL	BL	2H
10	SHILO	H	S	R-(BL)	2H
11	CARBERRY	P	FNL	BL	2H
12	HAMIOTA	P	FNL	BL	2H
13	ST. LAZARE	H	COL(C)	BL	2H
14	ERICKSON	H	FNL	DG	2H
15	ROBLIN	H	FNL	DG	2H
16	RIDING MOUNTAIN	S	FNL	GL	3H
17	GRANDVIEW	P	FNL	BL	2H
18	DUCK MOUNTAIN	S	FNL	GL	3H
19	KENVILLE	P	FNL	BL	2H
20	PORCUPINE MOUNTAIN	S	FNL	GL	3H
21	SWAN RIVER	P	FNL	BL-(DG)	2H
22	DAUPHIN	P	FNL	BL	2H
23	ALONSA	P	FNL	BL	2H
24	ST. ROSE	P	FNL	BL	2H
25	GYPSUMVILLE	P	FNL	DG	2H
26	GIMLI	P	C	DG	2H
27	LUNDAR	P	FNL	BL	2H
28	MCCREARY	P	FNL	BL	2H
29	MACGREGOR	P	COL	BL-(G)	1
30	ST. CLAUDE	P	S	BL-(R)	1
31	GLADSTONE	P	FNL	BL-(G)	2H
32	LANGRUTH	P	FNL	BL-(G)	2H
33	PORTAGE	P	FNL	BL-(R)	1
34	WINKLER	P	FNL	BL	1
35	WINNIPEG	P	C	BL-(G)	2H
36	EMERSON	P	FNL	BL	2H
37	STEINBACH	P	S	DG	2H
38	PINEY	P	S	BS-(GL)	2H
39	STEAD	P	S	DG-(O)	2H
40	WHITEMOUTH	P	O	O-(GL)	2H
41	GRINDSTONE	P	O	O	2H
42	BISSETT	H	O-C	O-(GL)	2H
43	WATERHEN	P	FNL	DG-(G)	2H
44	ASHERN	P	FNL	DG-(G)	2H
45	THE PAS	P	C	G-(R)	2H
46	WANLESS	P	C	G	3H
47	OVERFLOWING RIVER	P	O	O	3H
48	SWAN LAKE	P	FNL	BS	3H
49	CHITIK LAKE	P	C	BS-(GL)	3H
50	STURGEON BAY	P	O	O	3H
54	NOT CLASSIFIED				
61	NOT CLASSIFIED				

Figure 1. Agroecological Resource Areas of Southern Manitoba.

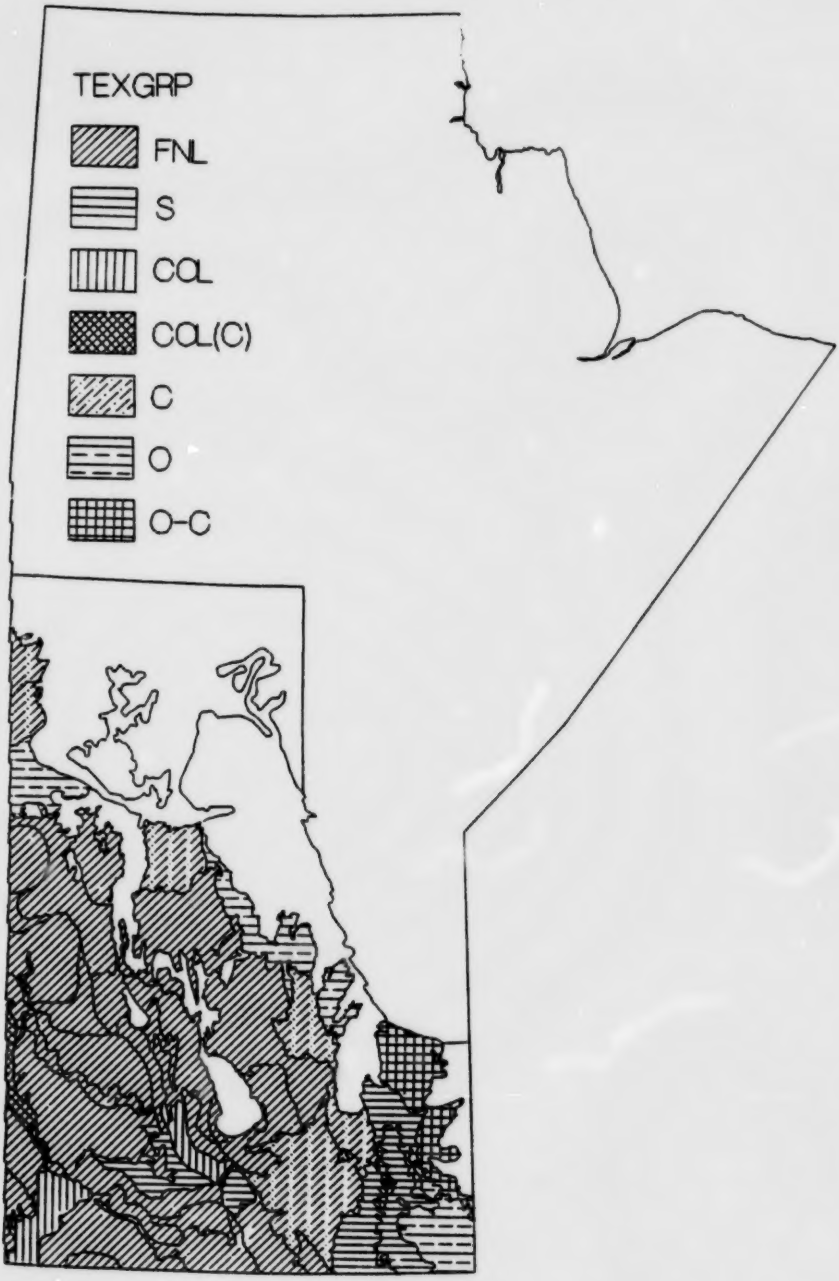

TEXGRP
FNL
S
COL
COL(C)
C
O
O-C

Figure 2. Derived Map of Textural Groups in Southern Manitoba.

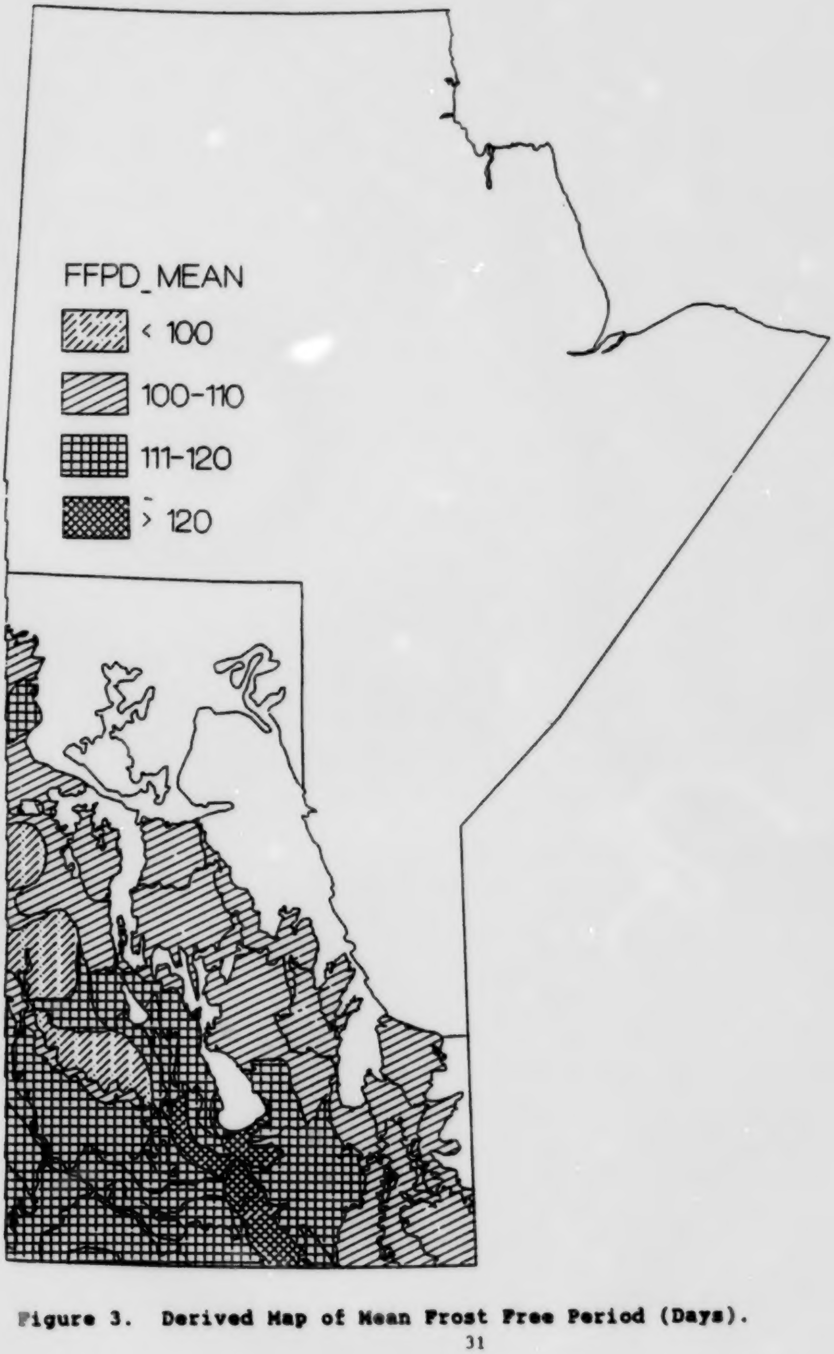

FFPD_MEAN
< 100
100-110
111-120
≥ 120

Figure 3. Derived Map of Mean Frost Free Period (Days).

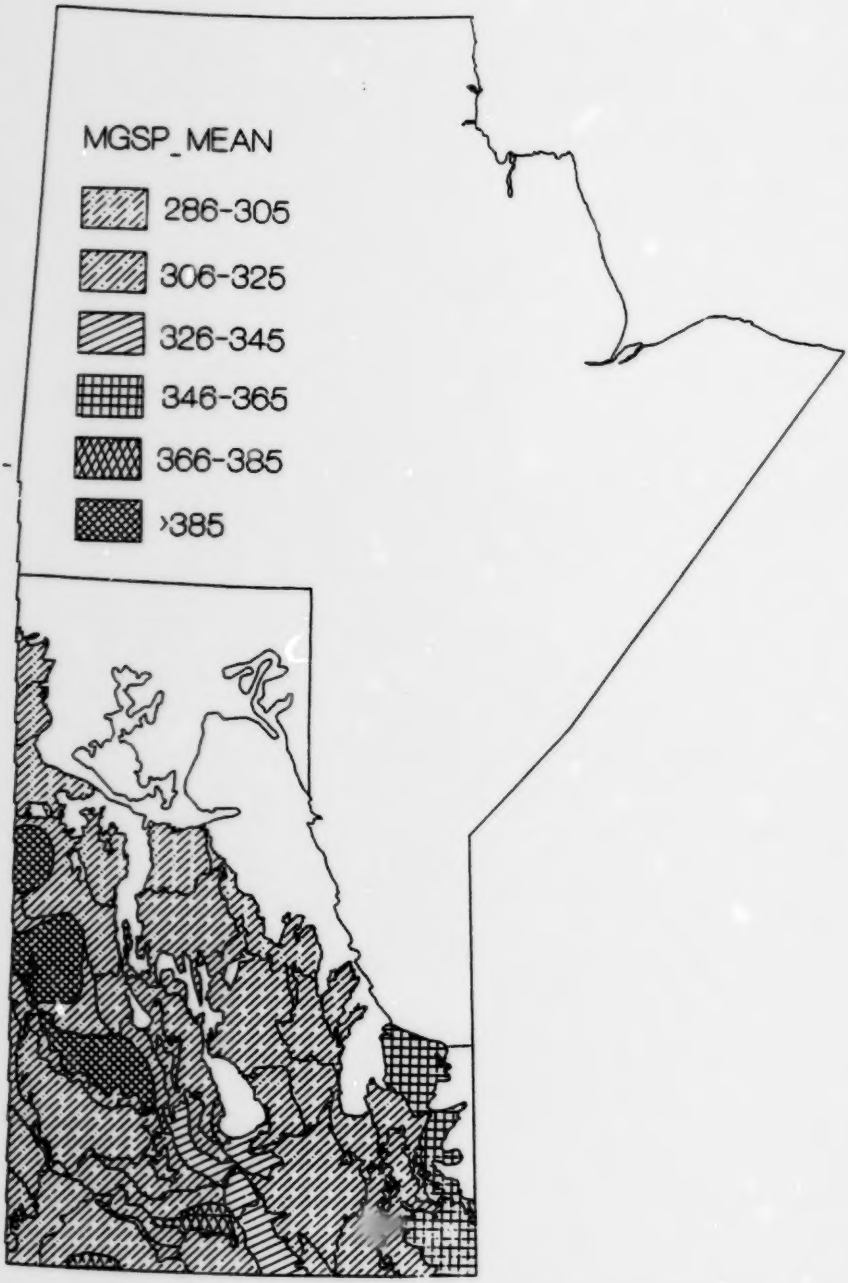

MGSP_MEAN
286-305
306-325
326-345
346-365
366-385
>385

Figure 4. Derived Map of Mean Growing Season Precipitation (mm).

THERMAL REGIMES OF CLAY SOILS IN MANITOBA

H. Veldhuis, G.F. Mills and R.G. Eilers
Canada-Manitoba Soil Survey

ABSTRACT

Soil temperature data from a transect of nine clayey soils extending from latitude 49°N to 56°17'N are presented.

Soil and vegetation conditions range from Black and Dark Gray Chernozems under subhumid grassland and grassland-forest transition to Gray Luvisols in the cool, more humid, Boreal forest.

Soil thermal regimes vary from cold to very cold with the most northerly Luvisol having permafrost within 1.5 m. Mean annual and mean summer soil temperatures (MAST and MSST) at 50 cm decrease northward at a rate of 0.9°C and 1.5°C per degree of latitude, respectively. The MAST gradients are nearly isothermal and shift toward 0°C with increasing latitude. The difference between September and January temperature is greatest in the Black soils and decreases with increasing latitude becoming smallest in the northern-most Gray Luvisol.

A moderately good correlation was found between the estimated location of the 0° isolines for MAST and MSST at 50 cm and boundaries of ecoclimatic regions and permafrost zones north of the study area.

Treed soils in the north are found to be cooler than cleared soils in both summer and winter. In the south treed soils are warmer in winter and cooler in summer than cleared soils.

INTRODUCTION

The range of latitude in Manitoba (49°N to 60°N) is associated with changing climatic conditions from south to north which result in significant ecological zonation across the province. Grassland and grassland-forest transition vegetation with Chernozemic Black and Dark Gray soils in the south, Boreal forest associated with Luvisolic soils in central regions and open Subarctic forest and Tundra associated with Cryosolic soils in the north are characteristic of the major ecoregions. Although clay soils do not occur over the total latitudinal range, they are extensive and cover some 7,000 Kha (Canada-Manitoba Soil Survey, 1989) between latitude 49°N and 58°N (Figure 1).

The objective of this paper is to describe the thermal regime of well to moderately well drained clay soils under forest cover as determined from nine benchmark sites along a south-north climatic gradient.

BIOPHYSICAL ENVIRONMENT

The clay deposits in Manitoba occur in a number of physiographically and geologically different areas (Figure 1). Most of the clay deposits are glacial Lake Agassiz sediments deposited during late Wisconsin time when glacial Lake Agassiz inundated large areas of Manitoba. Other clay

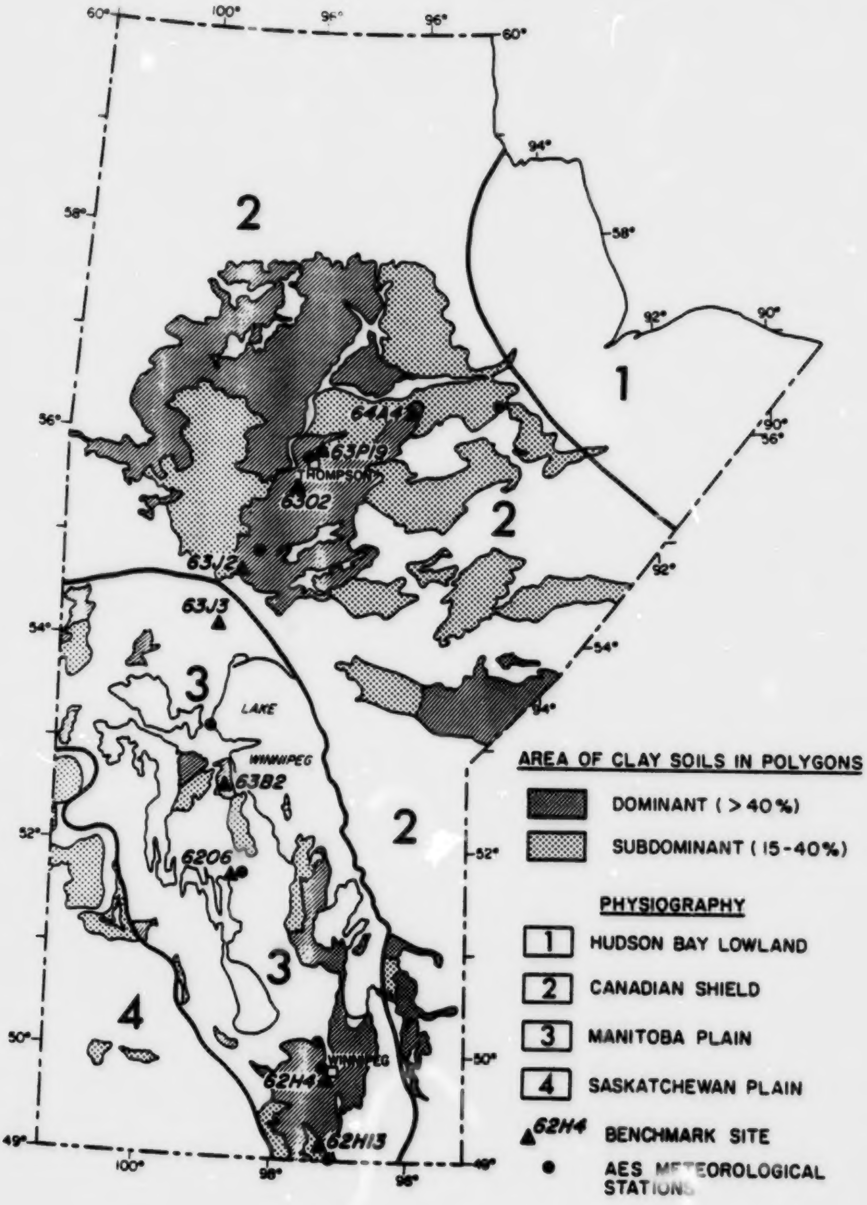

60°
100°
96°
60°
94°
58°
58°
92°
90°
1
56°
90°
56°
64A4
63P19
THOMPSON
6302
2
2
63J2
92°
63J3
54°
54°
3
LAKE
94°
WINNIPEG
63B2
52°
2
52°
6206
3
4
50°
50°
WINNIPEG
62H4
62H13
49°
100°
98°
96°
49°
AREA OF CLAY SOILS IN POLYGONS
DOMINANT (> 40 %)
SUBDOMINANT (15 - 40 %)
PHYSIOGRAPHY
1 HUDSON BAY LOWLAND
2 CANADIAN SHIELD
3 MANITOBA PLAIN
4 SASKATCHEWAN PLAIN
62H4 BENCHMARK SITE
AES METEOROLOGICAL STATIONS

Figure 1. Physiography and extent of clayey soils in Manitoba

deposits consist of clay till and lacustrine sediments from other proglacial lakes.

The lacustrine clays are fine clayey and dominantly moderately calcareous. In the southern part of Manitoba Cretaceous shale bedrock contributed mixed clay in which high shrink-swell smectite is co-dominant with illite. Illitic clay derived from Precambrian Shield rock is dominant to the north of Lake Winnipeg (Madden et. al., in prep.).

Climatically, Manitoba is characterized by a continental climate with relatively short, warm summers and long, cold winters with continuous snow cover. Available climatic data shows a gradual cooling and a shortened frost-free season with increasing latitude (Table 1).

Broad climate-soil-vegetation relationships are expressed in seven major ecoclimatic regions (Manitoba Ecoclimatic Region Working Group, 1985). The location of these regions is shown in Figure 2 and a brief summary of their characteristics is provided in Table 2.

MATERIALS AND METHODS

Location and Description of Study Transect

Location of the nine benchmark sites on the south-north transect is shown in Figure 1. Climatic data representative of the four ecoclimatic regions along the transect are provided in Table 1 and soil classification, site and vegetation characteristics are given in Table 2. The soils included in this study are classified as Black Chernozem, Dark Gray Chernozem and Gray Luvisol in the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey, 1987).

All soils have developed on lacustrine clay with the exception of the soil at site 6206 which developed on mixed clay and loamy morainal material.

Soil Thermal Regime

Soil Temperature - Soil temperatures were measured using thermocouples (1976-86) and thermistors (1986-89). Sampling frequency varied, but averaged 8 times per year in a random manner for the total period. Measurements from January and September of each year are used to represent a winter and a late summer measurement, respectively. However, January soil temperatures at lower depths have not yet reached minimum values and September soil temperatures near the surface have already started to cool, particularly at the northern sites.

Because of problems in correlating thermocouple data with thermistor date, thermal regime at each site was evaluated using the three years of thermistor data from the 20, 50, 100 and 150 cm depths (Table 3). The observed soil temperatures from June, 1986 to June, 1989 were fitted to an annual sine curve to mathematically calculate the best fitting line to the data and to derive a daily normal temperature for each day of the year (Reimer and Shaykewich, 1980). Then the mean annual soil temperature (MAST) and mean summer soil temperature (MSST) for the period June 1 to September 1 were calculated. Mean January and mean September soil temperature at each depth were calculated from the 1986 to 1989 mid-monthly data.

Table 1. Climatic Data From Selected Manitoba Weather Stations
(Atmospheric Environment Service, 1980)

Station	Latitude	Longitude	Mean temperature, °C			Mean Frost-free	Precipitation, mm	
	north	west	Annual	Jan.	July	period, days	Annual	May-Sept.
	Grassland transition Region, Gt							
Emerson	49°00'	97°16'	3.1	-18.2	17.5	125	515.7	343.6
Winnipeg	49°54'	97°14'	2.2	-19.3	19.6	122	525.5	350.2
Stonewall	50°07'	97°20'	1.5	-20.3	19.0	118	538.2	338.9
	Low Boreal subhumid Region, LBs							
Gypsumville	51°40'	98°44'	0.7	-20.7	18.0	101	418.4	271.2
	Mid Boreal subhumid Region, MBs							
Grand Rapids	53°11'	99°16'	-0.7	-21.8	17.7	101	442.7	267.9
	High Boreal subhumid Region, HBs							
Wabowden	54°55'	98°38'	-2.2	-24.6	16.9	105	464.2	297.6
Thompson	55°48'	97°52'	-3.9	-26.6	15.6	63	542.4	330.3
	Low Subarctic Region, LS							
Gillam	56°21'	94°42'	-4.6	-26.9	15.1	60	422.3	278.8

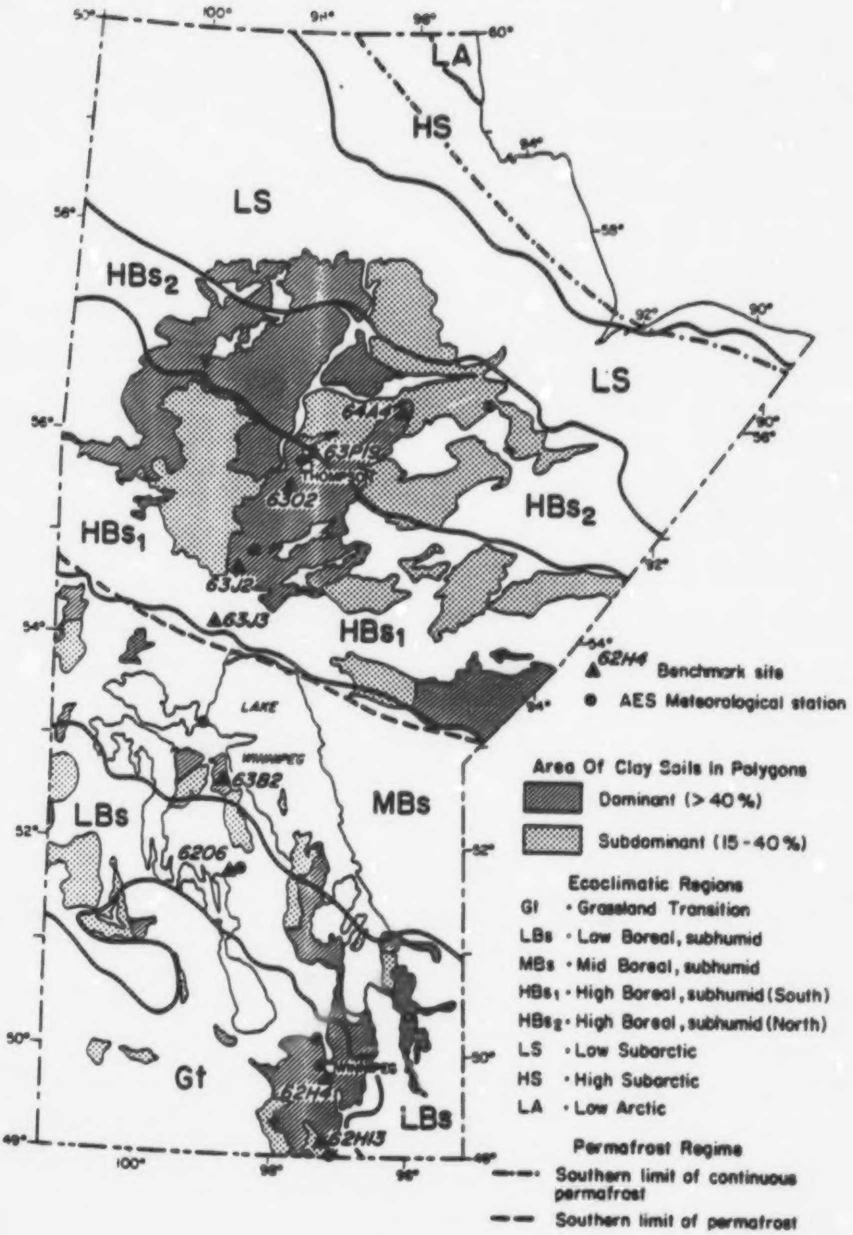

LA
HS
LS
HBs2
LS
HBs2
HBs1
HBs1
MBs
LBs
LBs
Gt
64A
63P
THOMPSON
6302
63J2
63J3
LAKE
WINNIPEG
6382
6206
WINNIPEG
62H
62H13
62H4 Benchmark site
AES Meteorological station
Area Of Clay Soils In Polygons
Dominant (> 40 %)
Subdominant (15 - 40 %)
Ecoclimatic Regions
Gt • Grassland Transition
LBs • Low Boreal, subhumid
MBs • Mid Boreal, subhumid
HBs1 • High Boreal, subhumid (South)
HBs2 • High Boreal, subhumid (North)
LS • Low Subarctic
HS • High Subarctic
LA • Low Arctic
Permafrost Regime
Southern limit of continuous permafrost
Southern limit of permafrost

Figure 2. Ecoclimatic regions, permafrost regime and location of AES stations and Benchmark sites.

Table 2. Ecoclimatic Regions and Benchmark Sites

Ecoclimatic Regions			Benchmark Sites			
Ecoclimatic Region	Soil Order or Great Group	Vegetation Type (natural)	Site No.	Soil Subgroup	Elev. m	Vegetation Type (actual)
Grassland transition(Gt)	Black Chernozem	Grassland-Aspen Parkland	62H13 62H14	Rego Black Orthic Black	234 227	Oak, aspen Oak, aspen
Low Boreal, subhumid(LBs)	Dark Gray Chernozem, Organic	Mixed Deciduous-Coniferous Forest	6206	Orthic Dark Gray	246	Aspen, oak, white spruce
Mid Boreal, subhumid(MBs)	Gray Luvisol, Organic	Mixed Forest	63B2	Orthic Gray Luvisol	248	Mixed white spruce-aspen
High Boreal, subhumid-1 (HBs$_1$)	Gray Luvisol, Brunisolic, Organic	Coniferous and Mixed Forest	63J3	Orthic Gray Luvisol	237	Black spruce, aspen, black poplar, balsam fir
			63J2	Orthic Gray Luvisol	225	Black spruce, black poplar
			6302	Orthic Gray Luvisol	220	Black spruce, jack pine
High Boreal subhumid-2 (HBs$_2$)	Gray Luvisol, Brunisolic, Organic, Cryosolic	Coniferous Forest	63P19	Solonetzic Gray Luvisol	210	Jack pine, black spruce, aspen
			64A4	Orthic Gray Luvisol (cryic)	180	Black spruce, few white spruce
Low Subarctic (LS)	Brunisolic, Cryosolic	Open Coniferous Forest	No site			
High Subarctic (HS)	Cryosolic, Brunisolic	Open Coniferous Forest & Tundra (shrub)	No site			
Low Arctic (LA)	Cryosolic	Tundra (shrub)	No site			

Soil thermal gradients - The latitudinal gradient in soil thermal regime is based on MAST and MSST values calculated from soil temperature measured at 50 cm for the soils at each benchmark site. Soil temperature data for the nine benchmark sites were grouped and averaged to provide an estimate of the rate of change with increasing northern latitude. Mean annual air temperatures along the transect are included in Figure 3. The vertical gradient for 1988 for each benchmark site is shown in Figure 4 as representative of a winter (January) and late summer (September) regime.

Thermal Regime of Clay Soils

The thermal regime of well drained clay soils under forest vegetation shows regional variability along the south-north transect and seasonal variation within the soil profile at each of the nine benchmark sites.

Regional thermal regimes in Manitoba - MAST values at 50 cm range from a high of 6.6°C in a Black Chernozem soil to a low of 0.2°C for the northern-most Luvisolic soil affected by permafrost (site 64A4, Table 3). MSST values vary from 12.6°C in the south to 1.1°C at the most northerly Luvisolic soil (site 64A4). Soil thermal regime of the Chernozemic Black soils in the Grassland transition region and the Dark Gray Chernozem soil in the Low Boreal region is cold according to soil temperature classes established for soil family classification (Agriculture Canada Expert Committee on Soil Survey, 1987). Thermal regimes characterizing the Luvisolic soils in the Mid and High Boreal region vary from cold at sites 63B2, 63J3 and 63J2 to very cold or cryic at sites 6302 and 63P19. A very cold thermal regime occurs at 150 cm at site 64A4 where the Luvisol soil contains permafrost.

The difference between MAST and MSST decreases with increasing latitude (Figure 3). Differences at 50 cm are greatest in the Black soils in the south (5.5°C at site 62H13 and 6.0°C at site 62H4) and least in the northern Luvisols (0.9°C at site 64A4) affected by permafrost. These differences are somewhat smaller at the 150 cm depth ranging from 1.4 to 2.6°C in the 4 southern sites to no difference in northern soils affected by presence of permafrost (Table 3).

As mean annual air temperature decreases, the difference between soil and air temperature tends to increase (Smith et al., 1964). MAST is generally about 3 to 4°C warmer than the corresponding air temperature at latitude 49°N, increasing to about 5°C warmer than the air temperature north of latitude 55°N (Figure 3). At these latitudes, summer soil temperatures are appreciably lower than the air temperature (Smith et al., 1964). In this study, the MSST at all sites (Table 3) is lower than summer air temperature recorded at nearby climatological stations (Table 1).

January soil temperatures are above 0°C at 50 cm throughout the Black Chernozemic clays (sites 62H13 and 62H4) and fall below 0°C in the Dark Gray (site 6206) and Luvisolic soils (Table 3). Minimum temperature in January at 150 cm remains above 0°C at all sites except the most northerly Luvisol (64A4). This soil has permafrost at 1.5 m and has a very cold thermal regime. The temperature of the permafrost at this latitude of northern Manitoba remains relatively constant at only a few tenths of a degree below 0°C. The maximum thickness of permafrost at this latitude has been reported to be about 15 m (Brown, 1970), but at this site it is very thin and not present in some years.

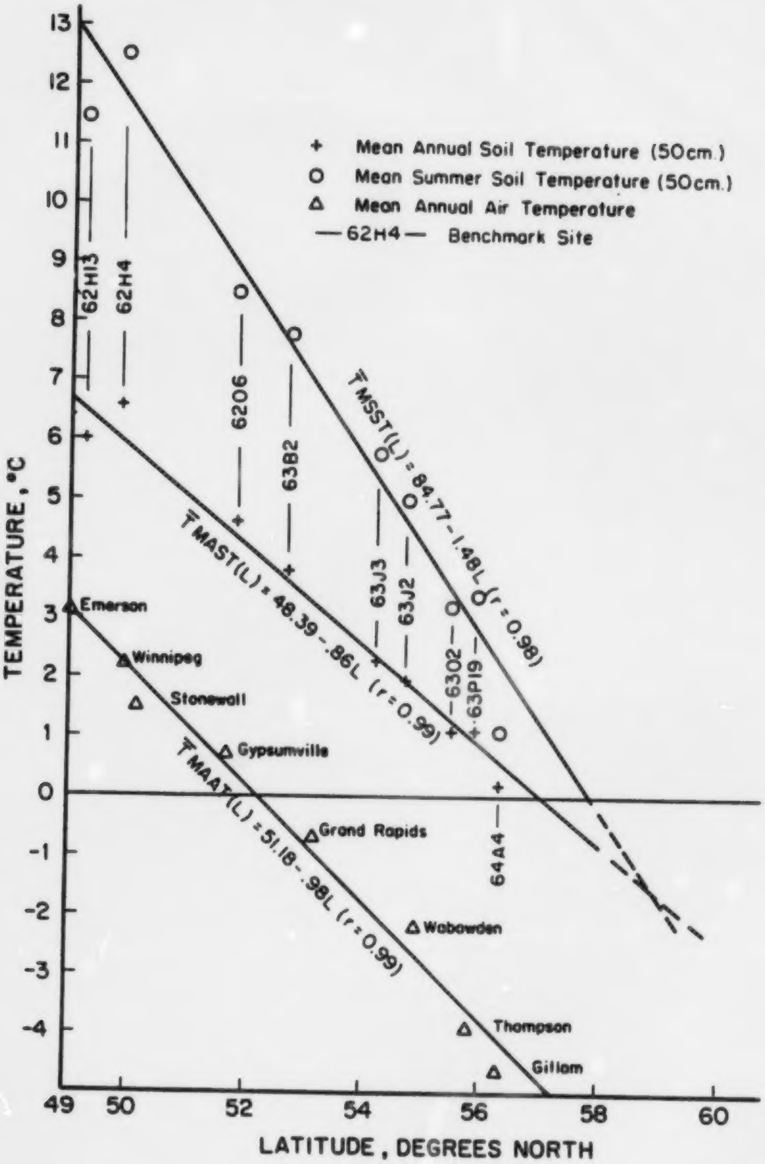


Figure 3. Scatter diagram and fitted lines of mean soil temperature at 50 cm and mean air temperature at 1.2 m.

Table 3. Mean Soil Temperatures at Benchmark Sites

Site No.	Depth (cm)	Mean Soil Temperature*				Mean Soil Temperature**	
		Annual	n	Summer	n	January	September
62H13	20	5.7	23	13.3	23	-1.7	12.5
49°08'N	50	6.0		11.5		0.3	12.2
97°15'W	100	6.0		9.0		2.4	11.2
	150	6.0		7.4		3.9	10.1
62H4	20	4.1	24	13.1	24	-	11.5
49°47'N	50	6.6		12.6		0.7	13.6
97°08'W	100	6.2		9.5		2.3	12.2
	150	6.3		7.9		4.5	11.4
62O6	20	4.8	19	10.9	19	-1.7	10.8
51°44'N	50	4.6		9.5		-0.3	10.4
98°46'W	100	4.3		7.6		1.2	9.4
	150	4.6		6.9		2.7	9.5
63B2	20	3.8	19	9.1	19	-2.0	8.8
52°39'N	50	3.8		7.8		-0.3	8.6
98°56'W	100	4.6		8.5		0.8	8.0
	150	4.2		6.8		1.7	7.4
63J3	20	2.7	18	7.3	18	-2.3	8.2
54°12'N	50	2.3		5.8		-0.9	7.4
99°11'W	100	2.8		5.0		0.7	7.5
	150	2.7		4.1		1.4	6.6
63J2	20	2.3	18	7.2	18	-3.3	7.9
54°42'N	50	2.1		5.0		-1.3	7.6
98°58'W	100	1.8		3.0		0.3	5.9
	150	1.7		2.2		0.9	4.9
63O2	20	1.6	29	5.1	29	-2.4	7.0
55°32'N	50	1.1		3.2		-1.3	5.5
93°03'W	100	1.3		2.4		-0.2	4.9
	150	-0.7		0.9		-0.7***	3.2
63P19	20	1.1	40	5.0	40	-2.8	6.3
55°55'N	50	1.1		3.4		-0.7	5.3
97°42'W	100	1.1		1.8		0.4	3.8
	150	0.9		1.0		0.6	2.3
64A4	20	0.6	15	3.7	15	-3.4	5.1
56°17'N	50	0.2		1.1		-1.0	1.9
96°09'W	100	0.1		0.1		-0.0	0.5
	150	-0.1		-0.1		-0.1	-0.0

---

* Mean annual and mean summer soil temperature calculated from thermistor observations, 1986-1989.

** Mean January and September soil temperature 1986-1989 n=3

*** January temperature derived from one observation due to sensor failure.

Latitudinal gradient - Soil temperature at 50 cm and the mean annual air temperature along the transect are shown on Figure 3. The regression equations for MAST and MSST at the 50 cm depth and the mean annual air temperature along the transect show that the rate of temperature change per degree of latitude ranges from a minimum of 0.9°C for MAST to a maximum of 1.5°C for MSST. These estimated rates of decrease in MAST and MSST follow the northward trend of mean annual air temperature which decreases at a rate of about 1°C per degree of latitude.

The predicted rate of change in regional soil temperature is most reliable when applied over the range of latitude included in the study. However, it is of interest to speculate on the estimated location of the 0°C isolines for MAST and MSST at 50 cm in relation to established biophysical conditions to the north of the study area (Figure 3). At these rates of change in soil temperature, a MAST of 0°C is estimated to occur at about latitude 57°N. This particular location corresponds reasonably well with the boundary between the High Boreal and Low Subarctic ecoclimatic regions. This boundary also coincides with the southern limit of widespread permafrost (Brown, 1970). The estimated location of a MSST of 0°C is very close to 58°N. This latitude along the transect is reasonably close to the boundary between the Low Subarctic and High Subarctic ecoclimatic regions. This boundary also approximates the southern limit of continuous permafrost as delineated by Brown (1970). Permafrost is characterized by some depth in the soil where the temperature will remain below 0°C over at least two consecutive winters and the intervening summer (Brown and Kupsch, 1974).

Vertical Thermal Regime - Vertical gradients in soil temperature vary with season and latitude. The soil thermal regimes for January and September, 1988 are plotted as a function of depth for each site in the transect (Figure 4). These soil temperature gradients are indicative of the maximum seasonal variation at each site. As would be expected, the vertical temperature gradient to the surface is negative in January and positive in September. The mean annual soil thermal gradients (1986-1989 data) also plotted for each site in the transect are nearly isothermal and shift toward 0°C with increasing latitude. The difference between September and January temperature decreases with increasing latitude as well as with increasing depth in the soil. The greatest temperature range in the upper 50 cm occurs in the Black soils at the two southern-most sites (62H13 and 62H4) and decreases only slightly to the north along the transect. The range in seasonal temperature variation below 50 cm decreases more rapidly with increasing latitude. The temperature difference is least at the northern-most Gray Luvisol (site 64A4). This soil has permafrost at lower depths in the profile and in some summers remains frozen between 50 and 100 cm. The temperature of permafrost at this latutude is only slightly below freezing (Brown, 1970) and is virtually isothermal with depth. The occurrence of the permafrost acts as a heat sink and provides a buffer against any large variation in soil temperature near the frost table.

Vegetation Cover Effects on Soil Thermal Regime - The thermal regime of clay soils is affected by the kind of vegetative cover. Comparison of thermal regime measured on clay soils within the same geographic area under forest vegetation and with the tree covered removed are shown in Figure 5. The comparison of Black soils under hardwood forest (64H4) and undergrass (64H6) indicates that in the south the treed site is warmer in winter and cooler in summer.

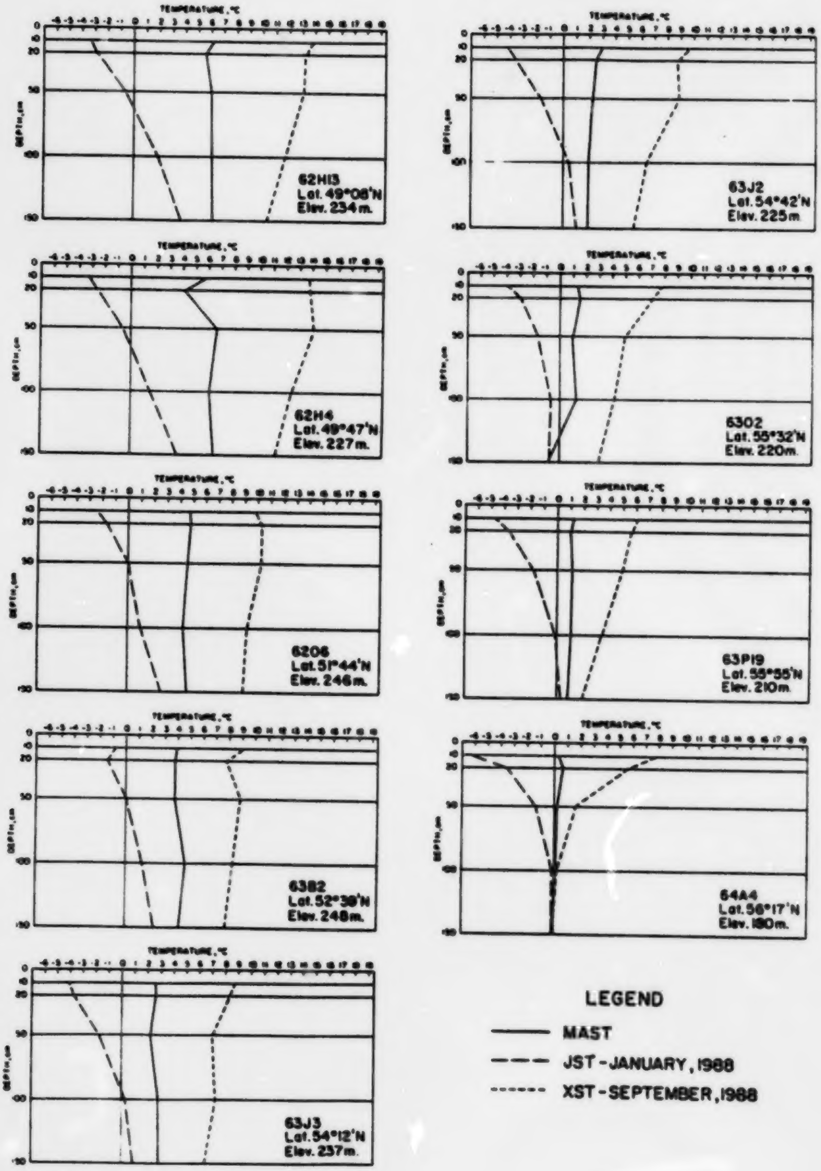


Figure 4. Vertical thermal gradients along south-north transect.

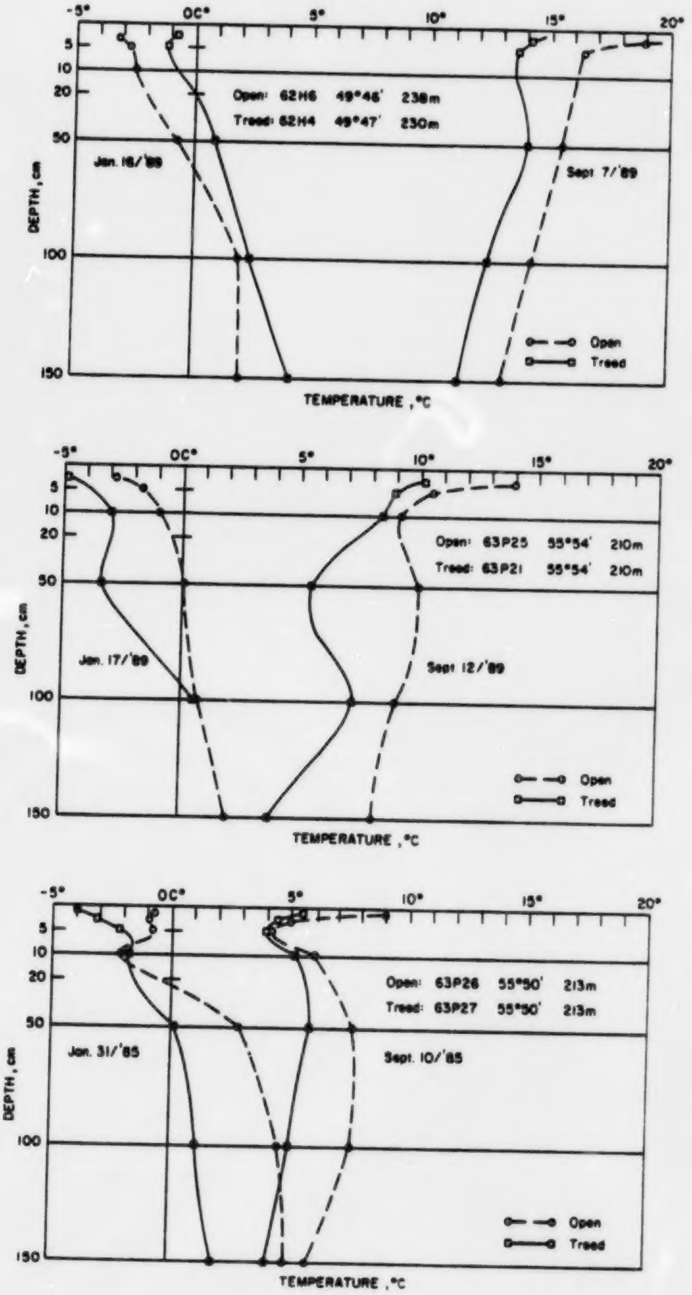


Figure 5. Comparison between vertical thermal gradients of treed and open sites.

Similar comparisons between forested (63P21 and 27) and cleared (63P25 and 26) Luvisols in the north show that the forested soils in the region are colder both in summer and winter. The difference in soil temperature regime between treed and cleared soils is significant at both southern and northern locations.

The difference between winter temperature regimes for northern soils can be accounted for by differences in snow depth on cleared and treed sites. On treed sites snow cover will be reduced as snow is intercepted by the tree canopy resulting in reduced insulation effect on the ground. In the summer the tree canopy will reduce the insulation of the soil surface resulting in less warming of the soils under forest cover. In the south the cause for the warmer thermal regime of cleared soils compared to that of treed soils probably is the same as that for northern soils. However, in the south, in winter the thermal regime of treed soils is warmer than that of cleared soils. This probably is due to the nature of the hardwood canopy which intercepts very little snow. Also, the snow cover often is thin or densely packed in open areas in the south. These combined factors likely result in higher insulation values of the snow cover under trees than that on cleared soils.

SUMMARY

Clay soils cover some 7,000 Kha in Manitoba between latitude 49°N and 58°N. Soil thermal regimes were examined in relation to climate at nine benchmark sites currently under forest in a south-north transect extending from latitude 49°N to 56°17'N. Warmer climate and subhumid conditions in the south result in grassland and grassland-forest transition vegetation characterized by Black and Dark Gray Chernozem soils. Cooler, more humid conditions associated with the Boreal forest extend northward from the grasslands to the southern edge of the Subarctic forest. Soil development in this region results in Gray Luvisol soils; the more severe climate associated with the northern-most Luvisols results in the occurrence of permafrost between 1 and 2 m.

The thermal regimes of clay soils vary from cold (MAST 2-8°C, MSST 8-15°C) for Black and Dark Gray Chernozems to cold and very cold (MAST -7 to 2°C, MSST 5 to 8°C) for the Luvisols. The most northerly clay soils have permafrost within 1.5 m resulting in a very cold thermal regime at this depth. The calculated rate of decrease in MAST (0.9°C/degree of latitude) and MSST (1.5°C/degree of latitude) shows a northward treed following the mean annual air temperature which decreases at a rate of about 1.0°C/degree of latitude.

Treed soils are cooler in summer than soils under forest cover both in the south and the north. However, in winter treed soils in the north are cooler than cleared soils while in the south the reverse is found.

ACKNOWLEDGEMENTS

The authors acknowledge the assistance and cooperation of the following people: Mr. C. Aglugub and Mr. N. Lindberg for data compilation and analysis; Mr. J. Griffiths and R. DePape for technical assistance in preparation of graphics; Ms. B. Stupak for typing the manuscript and Ms. D. Ceplis and her staff in Thompson for assisting in the field data collection.

This paper is largely excerpted from the paper "Thermal Regime of Clay Soils in Manitoba, Canada" by G.F. Mills, R.G. Eilers and H. Veldhuis, prepared for the VIth International Soil Correlation Meeting held in Regina, August, 1989. Beside soil climate data, also data on morphology of clay soils along the transect are presented. Anyone wishing to obtain a copy of this paper is invited to request one from the authors.

REFERENCES

Agriculture Canada Expert Committee on Soil Survey. 1987. The Canadian System of soil classification 2nd ed. Agric. Can. Publ. 1646, 164 pp.

Atmospheric Environment Service. 1980. Canadian Climate Normals. 1957-1980. Vol. 2, Temperature; Vol. 3, Precipitation; Vol. 6, Frost.

Bostock, H.S. 1970. Physiographic subdivisions of Canada. pp. 9-30 in Geology and Economic Minerals of Canada, Dept. of Energy, Mines and Resources Canada. Geological Survey of Canada, Economic Geology Report No. 1.

Brown, R.J.E. 1970. Permafrost in Canada. University of Toronto Press. 234 pp.

Brown, R.J.E. and Kupsch, W.O. 1974. Permafrost Terminology. National Research Council of Canada, Technical Memorandum No. 111, 62 pp.

Canada-Manitoba Soil Survey. 1989. Soil Landscapes of Canada-Manitoba, Land Resource Research Centre, Res. Br., Agriculture Canada, Ottawa, Ontario. Agric. Can. Publ. 5242/B (LRRC Cont. No. 87-16, report and map).

Ecoregion Working Group. 1989. Ecoclimatic regions of Canada, first approximation. Ecoregion Working Group of the Canada Committee on Ecological Land Classification, Ecological Land Classification Series 23. Sustainable Development Branch, Canadian Wildlife Service, Conservation and Protection, Environment Canada, Ottawa, Canada. 119 pp. and map.

Madden, J., Haluschak, P. and Mills, G.F. In Preparation. Clay mineralogy of some Manitoba soil parent materials. Canada-Manitoba Soil Survey, Winnipeg, Manitoba.

Manitoba Ecoclimatic Region Working Group. 1985. Ecoclimatic Regions of Manitoba, preliminary. Canada-Manitoba Soil Survey. Unpublished data, revised, 1987. Winnipeg, Manitoba.

Reimer, A. and C.F. Shaykewich. 1980. Estimation of Manitoba soil temperatures from atmospheric meteorological measurements. Can. J. Soil Sci. 60:299-309.

Smith, Guy D., Robinson, Luther H. and Swanson, Dwight. 1964. Soil temperature regimes - their characteristics and predictability. SCS-TP-144 Soil Conserv. Serv., U.S. Dep. Agr., Washington, D.C.

CHANGES IN BLACK SOILS FOLLOWING FOREST INVASION OF PRAIRIE

L.G. Fuller and D.W. Anderson
University of Manitoba and University of Saskatchewan

INTRODUCTION

The Aspen Parkland Ecoregion of Western Canada provides an opportunity to study changes in Black soils as a result of forest invasion of grassland soils. This ecoregion is a transitional zone between the Grassland and Southern Boreal Forest Ecoregions as indicated by a gradual change in climate, vegetation and soils. The effect of aspen invasion on Black prairie soils has been inferred from various studies (St. Arnaud and Whiteside 1964; Anderson 1972; Beke and Zwarich 1971; Pettapiece 1969). These studies were based on typical profiles from representative sites within each vegetative zone and did not consider physiographic differences. A more complete evaluation should involve changes over short distances and also the effect of physiography.

Evidence for the migration of forest vegetation onto Black soils is available from studies of grass opal. Grass opal is a deposit of silica (5-50 micrometers in size) occurring within epidermal cells of grasses (Rovner 1971; Blackman 1971). The opal remains in the soil as a "microfossil" when the plant dies. The ability of grasses to accumulate silica in large amounts relative to deciduous trees, the characteristic shapes of grass opal, and the relatively inert nature of grass opal permits grass opal to be used as a tool in reconstruction of vegetative history in prairie-forest transition studies (Witty and Knox 1964).

The surface 10cm of mineral soil can be expected to be most susceptible to a change from prairie to forest vegetation. This paper presents some changes in this layer of soil following forest invasion of prairie in an upland and lowland landscape.

MATERIALS AND METHODS

The sites were located approximately 100-km north of Regina, Sk. in the southern part of the Aspen Parkland. The upland landscape (LM) was located within the Last Mountain Upland (660m above sea level). The lowland landscape (WQ) was located approximately 16-km south-east of the LM site at the base of Last Mountain (560m). Both sites had never been cultivated. Water well records for the region indicated deep water tables (10-25m) at the LM site and water tables of 2-4m at the WQ site (Harder and Henry, 1989)

A transect proceeding from prairie into the aspen forest was located at each site. The transect consisted of soil descriptions and a volumetric core sample of the surface 10cm of mineral soil, at 3m intervals. The LM transect was 81m long and the WQ transect was 57m long.

Grass opal analysis involved separation of the silt fraction by sedimentation; preparation of slides by sprinkling the silt over a drop of immersion oil; and finally, direct counting of the number of grass opals in 2000 total grains at 512x magnification on a petrographic microscope.

Bulk density was obtained from the weight of the soil core after correction for hygroscopic moisture. pH was determined on a 1:1 soil:water mixture. Cation exchange capacity (CEC) and exchangeable cations were determined using 0.25M$BaCl_2$ buffered at pH 8.0 as the saturating solution. The Ba was replaced from the exchange using 0.1M ammonium acetate buffered at pH 7.0.

Total carbon was determined using an automated combustion instrument (LECO 600-CHN). Inorganic carbon was determined by the method of Tiessen et al. (1983). Organic carbon was calculated as the difference between total and inorganic carbon. Nitrogen was determined by the Kjeldahl method (Bremner and Mulvaney 1982). Total phosphorus was determined by alternating 30 minute digestions at 360 C in concentrated sulfuric acid followed by 35% hydrogen peroxide. Acid-extractable phosphorus was determined by shaking 1 g of soil in 50mL of 0.5M sulfuric acid for 16 hours. Both total and acid-extractable phosphorus in the digests were determined colorimetrically (McKeague 1978).

RESULTS AND DISCUSSION

Grass Opal Analysis

Similar quantities of grass opal occur in prairie and forest soils at both sites (Figure 1). This indicates that grassland occupied the transects for much of their history, and that the present boundary is well into former grassland. No conclusions can be drawn regarding the position of the prairie-forest boundary in the past due to the variable opal content of the soils. The differences in opal content at each point are thought to reflect differences in grass productivity within grassland and therefore variability in silica accumulation. Lower opal contents for sites 20 and 21 coupled with higher opal contents at sites 16 to 19 may reflect a previous prairie-forest boundary at LM (Figure 1). The transect at WQ shows higher opal contents for sites 17 to 20 which occur in a depression and can be expected to be the result of greater productivity.

It is evident that a significant amount of grass opal exists within the surface 10cm of the forest soils indicating that grassy vegetation had occurred along the entire length of the transect. It appears that the present prairie-forest boundary has been estabished recently and that the soils under forest vegetation likely resembled prairie soils at one time in their history. Therefore differences between prairie and forest soils will reflect the effect of forest invasion of prairie at the two sites.

Bulk Density, pH and CEC

At LM, the advance of aspen onto the prairie has resulted in decreased pH, increased bulk density, and decreased CEC in the surface 10cm (Figure 2). Exchangeable Ca, Mg, and K also decreased, with exchangeable Na at very low concentrations in all soils.

At WQ, bulk density, CEC, exchangeable Ca, Mg, and K showed no trend of increase or decrease except in the depressional soils (Figure 3).

The forest soils outside the depression maintained a neutral to slightly alkaline pH similar to the prairie soils, but in the forested depression the soils were acidic.

Carbon, Nitrogen and Phosphorus

The amounts of organic carbon (OC), nitrogen (N) and total phosphorus (TP) in the surface 10 cm of mineral soil differed in prairie and forest soils at LM (Figure 4). The amount of OC, N, and TP declined immediately at the present prairie-forest boundary, whereas acid-extractable phosphorus (AEP) remained fairly constant. The decline in OC and N with distance into the forest is best described with an exponential curve (r^2=0.79 and 0.81, respectively)(Figure 5). The decrease in TP, unlike OC and N, can not be described by an exponential curve. The decline in TP and the constant level of AEP result in a diminished difference between TP and AEP. The difference between TP and AEP can be assumed to be an estimate of organic P (Saunders and Williams 1955). The reduction of TP in the forest appears to be mainly a result of losses of organic P. This agrees with the OC and N data as indicated by a strong correlation between OC and TP-AEP (Figure 6). The loss of organic P from forest soils has been postulated by Frossard et al.(1989).

The situation at WQ is quite different. The soils under aspen do not experience a loss of OC, N or TP from the surface 10cm except in the depression (48-57m) where OC, N, and TP are less abundant (Figure 7).

The mass-balance of TP in the surface 10cm for the two transects exhibits the same trend as the total amount of TP along the transects (Figure 8). This mass-balance approach compares the ratio of the weight of TP/weight of non-carbonate sand+silt in the parent material to the same ratio in the surface 10cm layer. This approach requires the assumptions that (1) the parent material is uniform; and (2) the weight of sand+silt in a given soil horizon does not change with pedogenesis. It is evident that losses of TP occurs immediately at the prairie-forest boundary at LM with an average loss of 40 to 50% from the surface 10cm. No loss of TP occurs at WQ except in the depression where TP losses from the surface 10cm are large.

Forest invasion of prairie at LM results in enhanced eluvial development as indicated by the development of Ae and Bt horizons under forest. This eluvial development is accompanied by loss of exchangeable bases and organic materials from the surface of the soil. At WQ there is no indication of eluvial development under the forest except in the depression. Moving from the prairie into the forest at WQ, there is a shift from an Ah/Bm horizon sequence to an Ahk/AC horizon sequence and the absence of a B horizon. These calcareous soils under forest have been referred to in the past as "Wooded Calcareous" soils (Mitchell et al. 1950). Detailed analysis of a "Wooded Calcareous" profile at WQ showed that the carbonate mineralogy consists of predominantly finely divided calcite with very little dolomite in the surface 60cm (data not shown). It appears that, outside the depression, an infusion of secondary carbonate has occurred under forest vegetation at WQ. The source of this secondary carbonate is postulated to arise from enhanced Ca-cycling by the aspen from a gypsiferous horizon at 60-80cm. This is suggested by large amounts of soluble Ca and sulfate present in the leaf litter of the "Wooded Calcareous". Precipitation of gypsum in subsoils of soils adjacent to recharge depressions has been shown by Steinwand and Richardson (1989). The lack of eluvial development and occurrence of secondary calcite in the calcareous forest soils at WQ contrast sharply with the leached, acidic soils under forest at LM. It appears that leaching potential is a major factor controlling the changes which will occur in the soil.

SUMMARY AND CONCLUSIONS

The effect of forest invasion on Black prairie soils is dependent on the nature of the landscape in which the transition occurs. In the upland landscape, where the leaching potential is presumed to be strong, eluvial development occurs and the soils are gradually changed to Dark Gray soils and eventually to Luvisolic soils. This is accompanied by losses of organic carbon, nitrogen and phosphorus from these soils as they become progressively more acidic and more dense.

In the lowland landscape, where strong leaching is restricted to depressional areas, the Black prairie soils persist under the aspen. Organic carbon, nitrogen, and phosphorus as well as pH and bulk density are maintained at similar levels relative to the prairie soils. However, in the depression where eluvial development is strongly expressed, the soils exhibit characteristics similar to the forest soils of the upland. Therefore, it appears that the degree of leaching in the soils largely controls the effect of aspen invasion on Black prairie soils.

Based on the grass opal content of the LM soils, it appears that changes in the soil surface may take place more rapidly than previously thought. The prairie soils at WQ appear to be more able to resist the degradative changes which have occurred at LM possibly due to decreased leaching potential and enhanced base cycling. Landscape-soil relationships are important factors affecting the nature of the soil and therefore must be considered in pedological research.

LITERATURE CITED

Anderson, D.W. 1972. The characteristics of organic matter of grassland, transitional and forest soils. Ph.D Thesis. Univ. of Saskatchewan, Saskatoon. Univ. Microfilms. Ann Arbor, Mich. (Diss. Abstr. 72-31368).

Beke, G.J. and M.A. Zwarich. 1971. Chemical and mineralogical characteristics of cutans from B horizons of three Manitoba soils. Can. J. Soil Sci. 51:221-228.

Blackman, E. 1971. Opaline silica bodies in the range grasses of southern Alberta. Can. J. Bot. 49:769-781.

Bremner, J.M., and C.S. Mulvaney. 1982. "Nitrogen-Total". Chapter 31 in "Methods of Soil Analysis Part 2-Chemical and Microbiological

Properties" 2nd edition. A.L. Page, R.H. Miller, and D.R. Keeney (eds.). Agronomy Monographs No.9. Published by American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin, U.S.A. pp. 595-624.

Frossard, E., J.W.B. Stewart, and R.J. St. Arnaud. 1989. Distribution and mobility of phosphorus in grassland and forest soils of Saskatchewan. Can. J. Soil Sci. 69:401-416.

Harder, H. and J.L. Henry. 1989. Map of water wells, Strasbourg 72P12. Sask. Inst. of Pedology, Univ. of Sask., Saskatoon, Saskatchewan.

McKeague, J.A. (ed.) 1978. Manual On Soil Sampling And Methods Of Analysis. 2nd edition. Can. Soc. Soil Sci., Ottawa, Ontario, Canada.

Mitchell, J., H.C. Moss, and J.S. Clayton. 1950. Soil Survey of Saskatchewan. Saskatchewan Soil Survey Report No. 13. University of Saskatchewan, Saskatoon, Saskatchewan.

Pettapiece, W.W. 1969. "The Forest-Grassland Transition" in Pedology and Quaternary Research, Univ. of Alberta, Edmonton, S. Pawluk (ed.), pp.103-113.

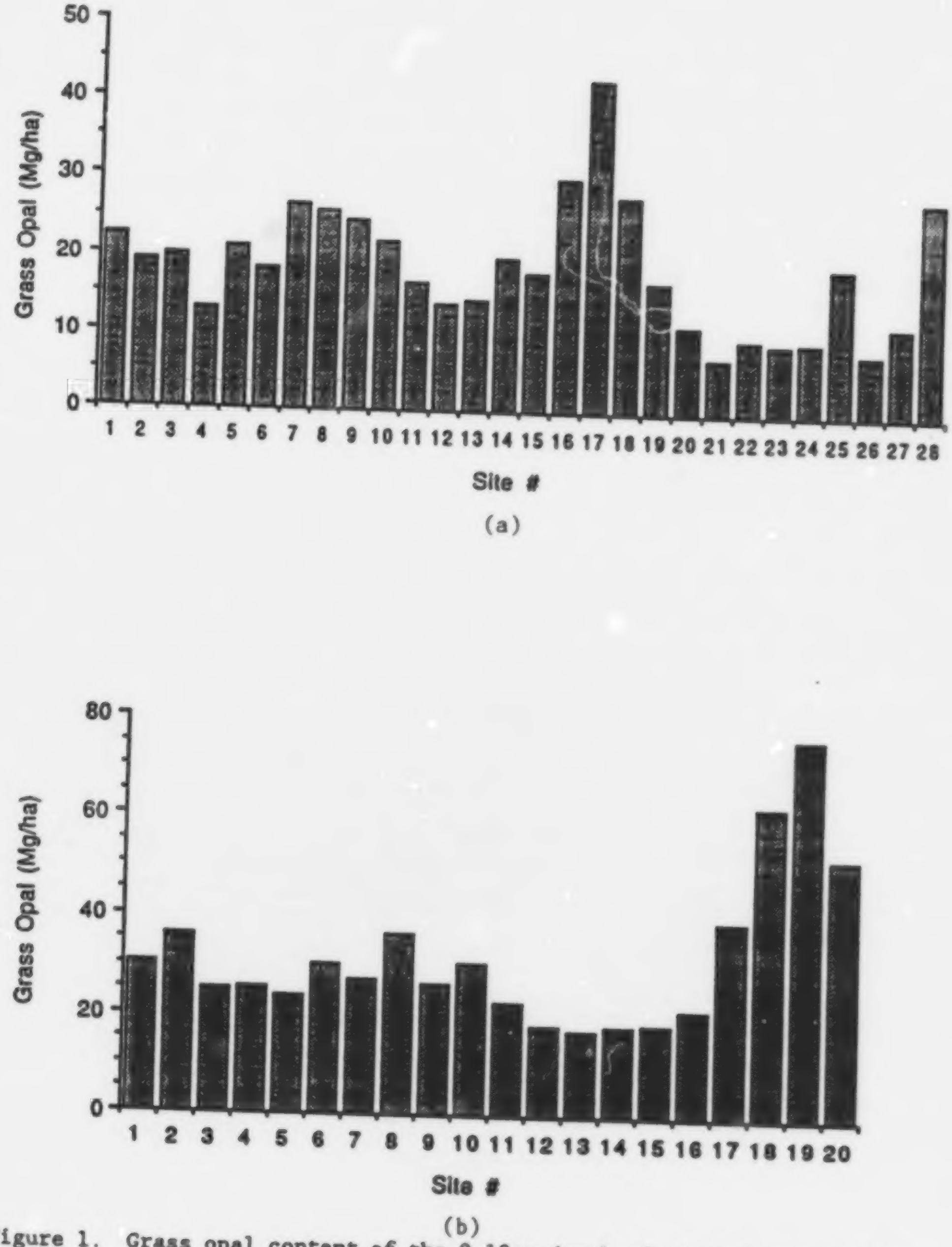
Rovner, I. 1971. Potential of opal phytoliths for use in paleoecological reconstruction. Quat. Res. 1:343-359.

St. Arnaud, R.J., and E.P. Whiteside. 1964. Morphology and genesis of a Chernozemic to Podzolic sequence of soil profiles in Saskatchewan. Can. J. Soil Sci. 44:88-99.

Steinwand, S.L., and J.L. Richardson. 1989. Gypsum occurrence in soils on the margin of semipermanent prairie pothole wetlands. Soil Sci. Soc. Am. J. 53:836-842.

Tiessen,H., T.L. Roberts, and J.W.B. Stewart. 1983. Carbonate analysis in soils and minerals by acid digestion and two-endpoint titration. Commun. In Soil Sci. Plant Anal. 14:161-166.

Witty, J.E., and E.G. Knox. 1964. Grass opal in some chestnut and forested soils of north central Oregon. Soil Sci. Soc. Amer. Proc. 28:685-688.



(a)

(b)

Figure 1. Grass opal content of the 0-10cm depth of mineral soil; (a) LM transect (present prairie-forest boundary is located between sites 4 and 5); (b) WQ transect (present prairie-forest boundary is located between sites 7 and 8).

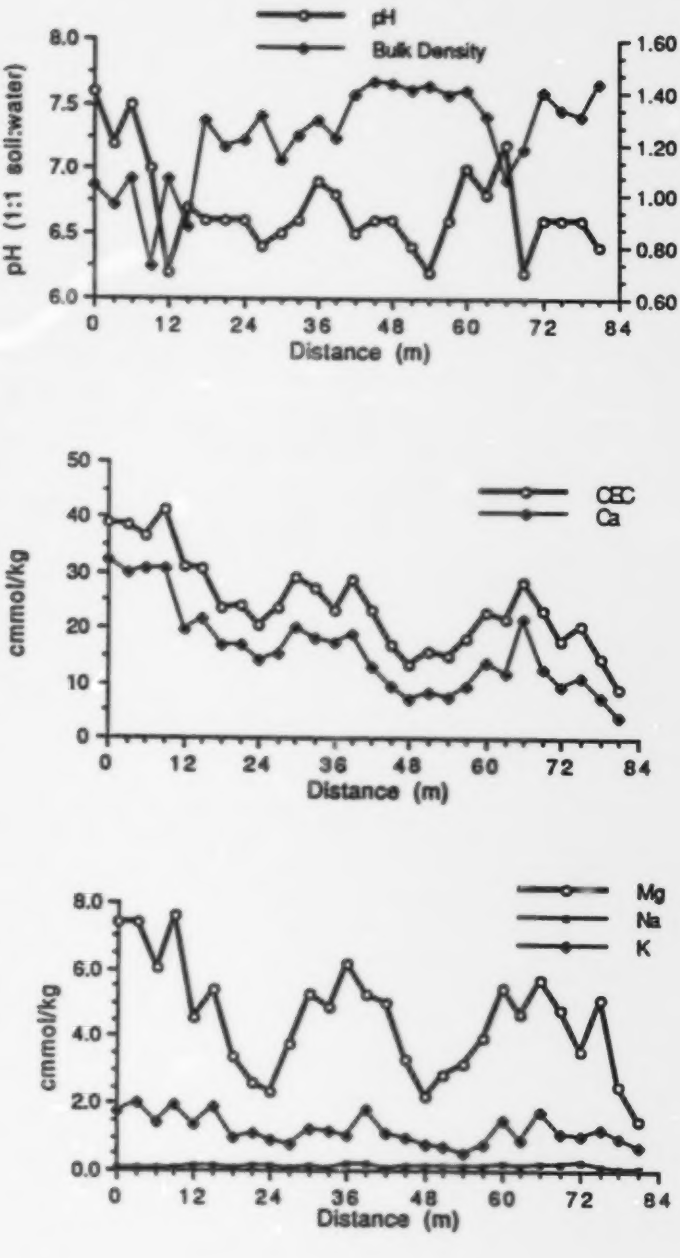


Figure 2. pH, bulk density, CEC, and exchangeable cations for the 0-10cm depth along the LM transect. The present prairie-forest boundary is located between 9 and 12m along the transect.

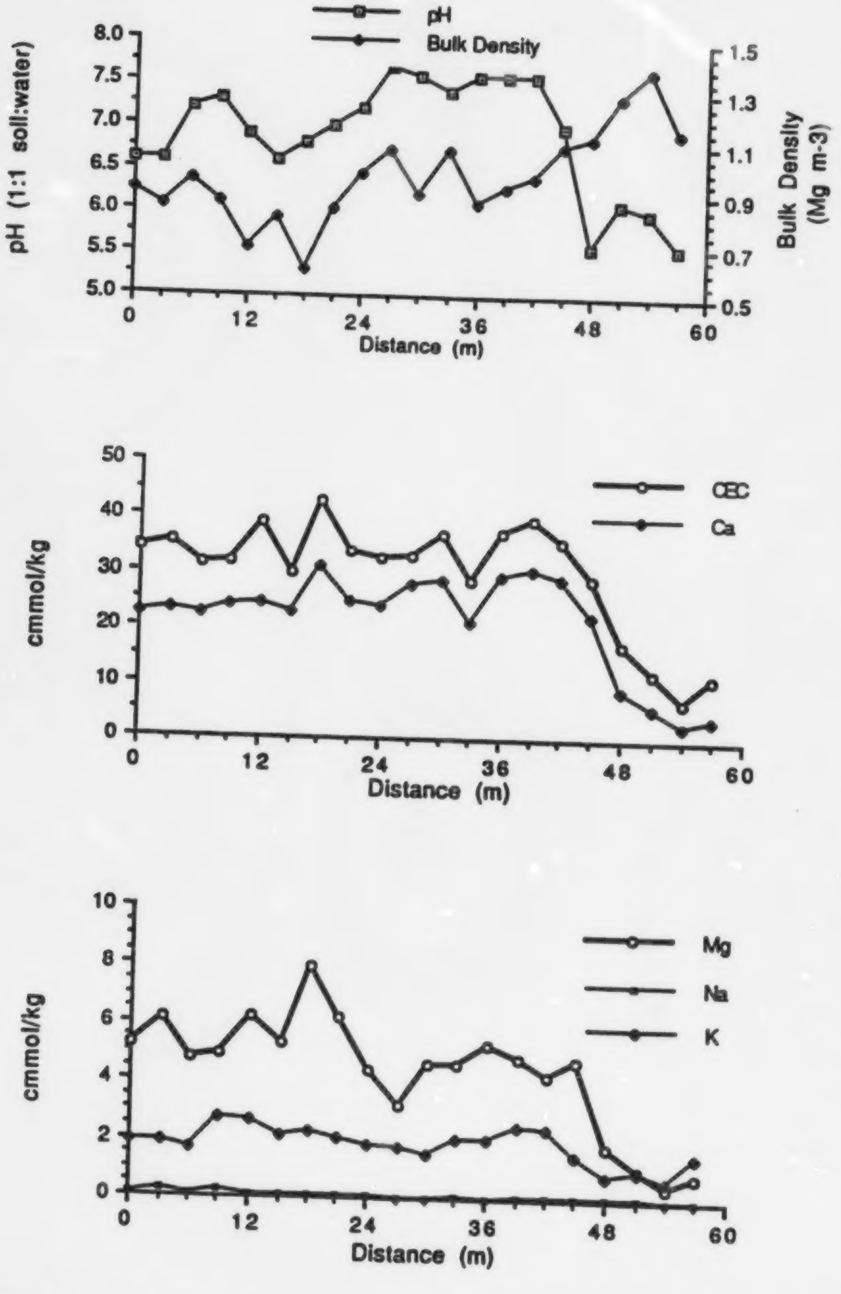


Figure 3. pH, bulk density, CEC, and exchangeable cations for the 0-10cm depth along the WQ transect. The present prairie-forest boundary is located between 18 and 21m along the transect.

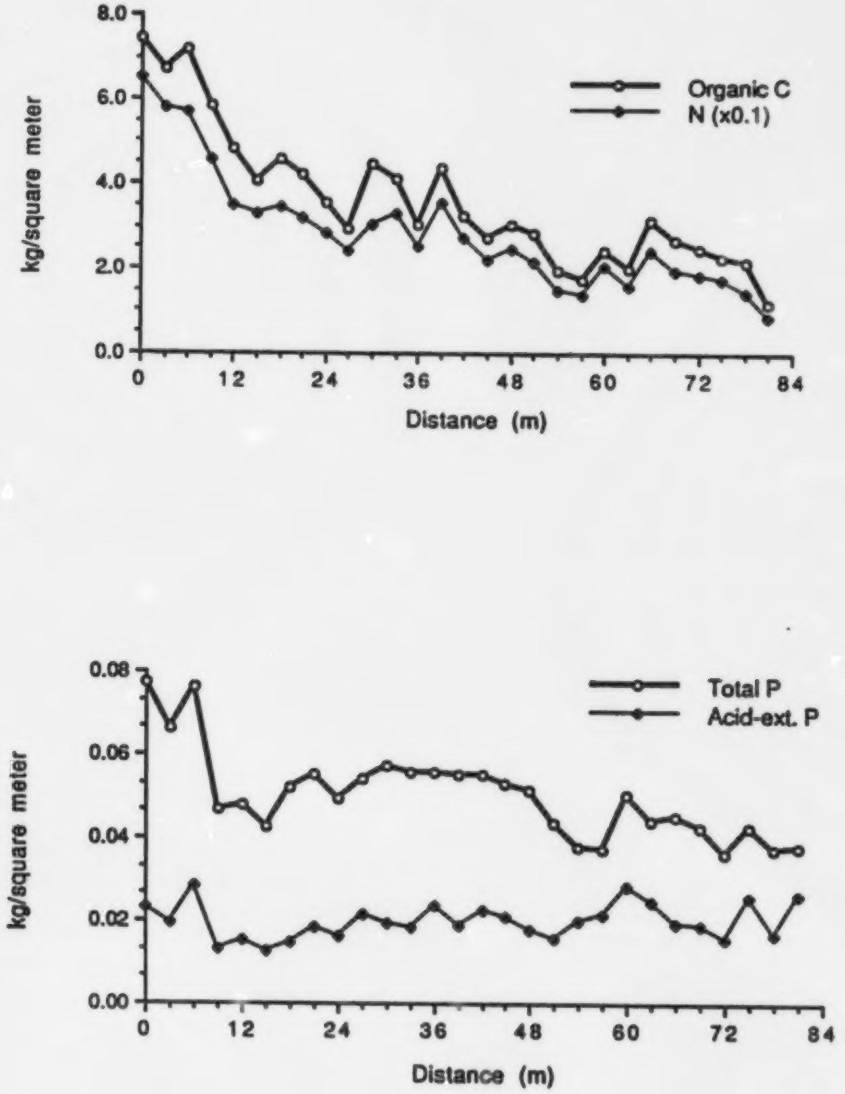
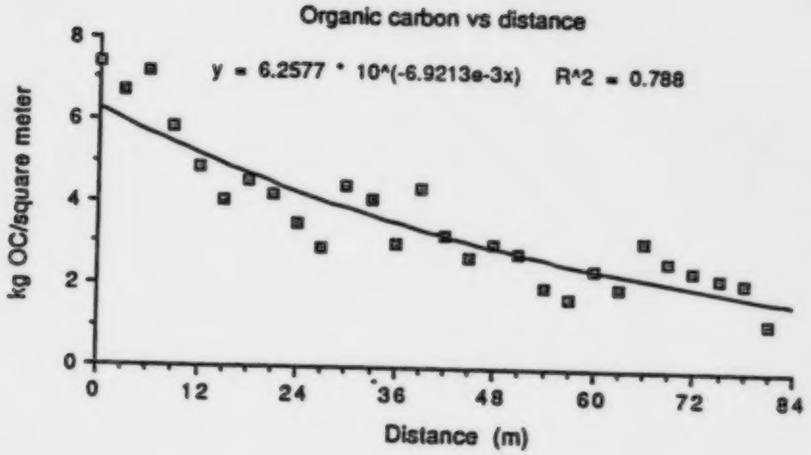


Figure 4. Organic carbon, nitrogen, total phosphorus and acid-extractable phosphorus for the 0-10cm depth along the LM transect.



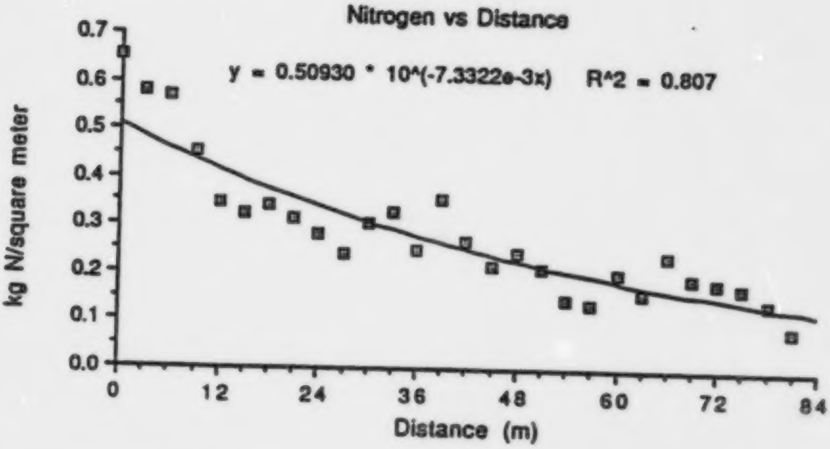
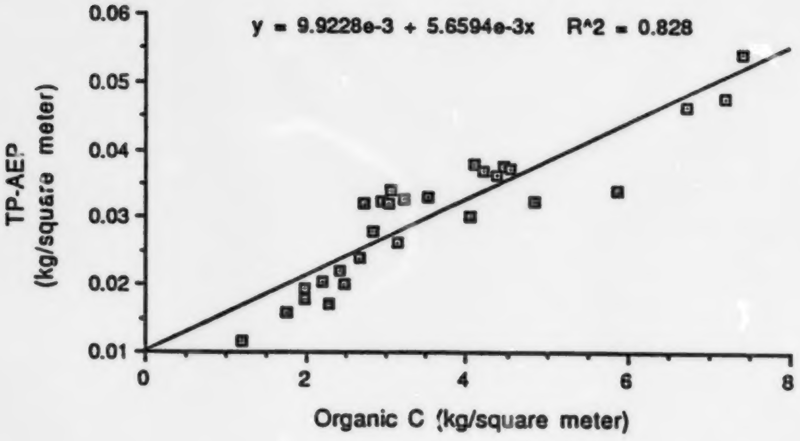


Figure 5. Organic carbon and nitrogen in the 0-10cm depth vs. distance along the LM transect.



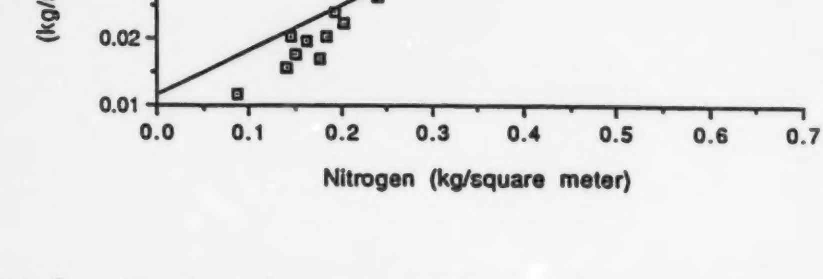
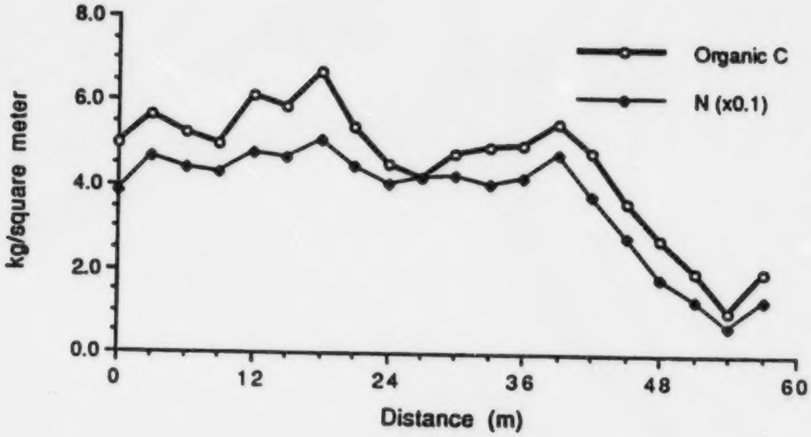


Figure 6. Organic carbon and nitrogen in the 0-10cm depth vs. the difference between total phosphorus and acid-extractable phosphorus for



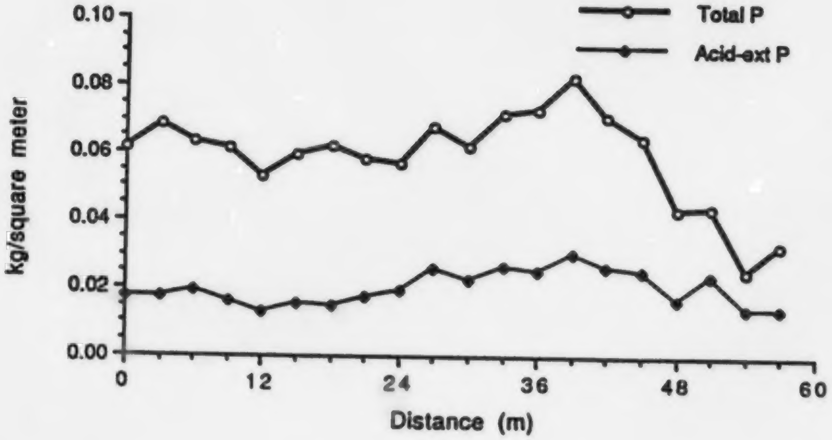
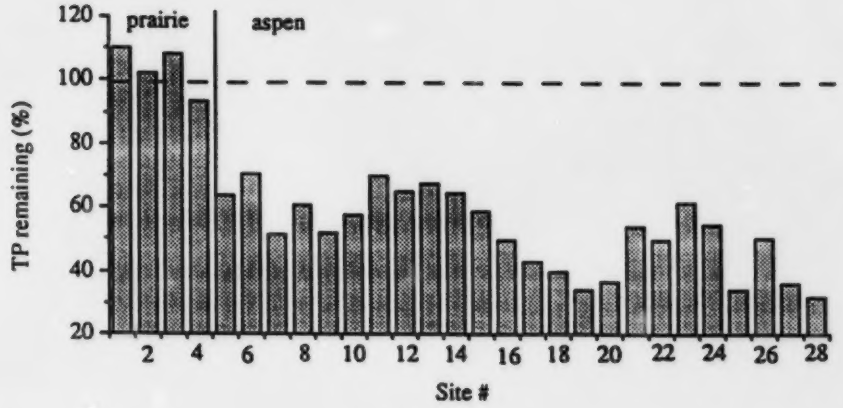
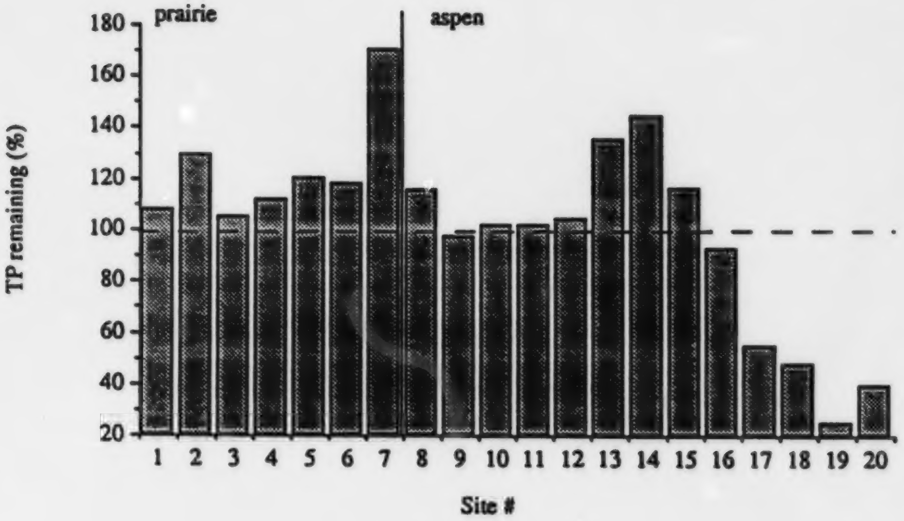


Figure 7. Organic carbon, nitrogen, total phosphorus, and acid-extractable phosphorus in the 0-10cm depth along the WQ transect.



(a) LM Transect



(b) WQ Transect

Figure 8. Total phosphorus remaining in the 0-10cm depth as a percentage of the original mass of phosphorus, (based on the non-carbonate sand+silt index) for (a) the LM transect; (b) the WQ transect.

EFFECTS OF FREEZING ON SULFATE SALTS IN NORTH DAKOTA SOILS AND WETLANDS

by

J.L. Richardson, J.L. Arndt and J.W. Enz

INTRODUCTION

This paper is a preliminary paper with more complete data to be published elsewhere. Cooling and freezing are techniques used in the sulfate salt industry to separate Glauber salts (mirabilite $Na_2SO_4 \cdot 10H_2O$) from epsom salts (epsomite $MgSO_4 \cdot 7H_2O$) and other brine constituents (Last and Schweyen, 1983). Figure 1 presents the temperature dependent solubility relationships and stability fields of the major Mg and Na sulfate salts. By controlling density, temperature and brine composition a nearly pure sodium sulfate can be harvested. In saline seeps the stability of sulfate evaporite minerals and the relative abundance of their associated ionic constituents in soil extracts is also strongly affected by temperature changes (Keller et al. 1986a, 1986b; Timpson et al. 1986; Timpson and Richardson 1987). A similar but annual separation of Mg and Na salts should occur in soils and pond water during fall and winter freeze-up if the solution has sufficiently high salt content and contains abundant sulfate.

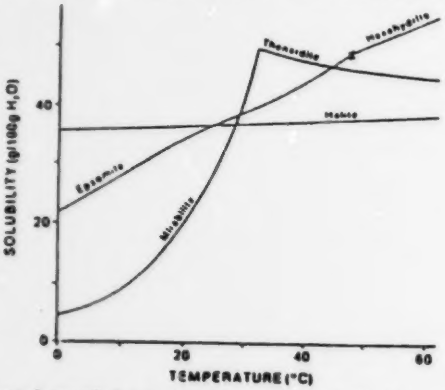


Figure 1. Relationships between solubility and temperature for some common efflorescent salts (After Timpson et al., 1986).

Freezing of saline lakes can also have other unexpected consequences. Sublimation, the transition of a substance directly from the solid state to the vapor state, may explain the observed release of crystalline salts from the ice of a saline pond emplaced in ice-thrust hummocky moraine in east-central North Dakota. During early winter sampling of this pond we noted drifts of salt on the ice surface in emergent vegetation. The dune-like appearance and position of the salt on top of the ice plus the absence of other salt sources suggests that original ice-entrapment of salt occurred The entrapment was followed by later release through sublimation of the pond ice (Arndt and Richardson 1985).

This paper investigates the influence of freezing of sulfatic waters on salinization and segregation of Mg and Na in a natural setting associated with brackish to saline ponds in east-central Nelson County, North Dakota.

PROCEDURES

The identity of evaporite salts collected in winter was determined by x-ray diffraction using the techniques of Keller et al (1986a). Monthly to bimonthly samples of near-surface groundwaters were collected from hydric soils peripheral to the saline and brackish wetlands using several passive, capsule-type groundwater collectors (Arndt and Richardson 1988, 1989). The study wetlands are emplaced in calcareous, sulfate-rich till typical of the Northern Plains, the weathering of which results in strongly sulfatic groundwater (Hendry et al. 1986). Electrical conductivity (EC), pH, and soluble ions (CO_3, HCO_3, Cl, SO_4, Ca, Mg, Na, and K) were determined in salt (dissolved in a known quantity of deionized water), ice, and water samples using standard methods (Soil Survey Staff, 1984).

To investigate the magnitude of sublimation as a potential source of crystalline salts over winter, direct measurements of weight loss due to ice sublimation from white plastic pans filled with water and frozen were made during January of 1985 and 1987. Days where snowfall covered the pans and days where the temperature was above freezing were excluded from the results.

RESULTS AND DISCUSSION

Sublimation ranged from 0.06 to 0.69 mm H_2O per day during 12 days in January, 1985. During January, 1987 sublimation ranged from 0 to 0.73 mm H_2O per day during 18 days. The average for all measured days was 0.31 mm per day, a value probably inflated because days with precipitation (snow) or days with periods above freezing were excluded. However, when related to a 20 acre (8 ha) pond similar to saline pond (20) (Table 1), this represents a loss of over 25 000 $L \cdot day^{-1}$ of water. If the concentration of salt in the ice is 10 $g \cdot L^{-1}$ (EC approx. 10 $dS \cdot m^{-1}$, Table 1), this represents a release of over 250 $kg \cdot day^{-1}$ of salt from this wetland. Even if sublimation values are halved, the potential exists for large quantities of salt to be released.

The effect of freezing as a concentration mechanism can be seen in the conductivity and the relative ionic composition of selected water and salt samples from both the brackish wetland (18) and the saline wetland (20) (Table 1). The data from wetland (20) show that the EC of surface ice was 2/3 that of fall water, yet winter water collected under the ice exhibited conductivities 2-3 times greater than fall. Similar trends are noted in wetland (18). These data suggest that dissolved solids are exiting from freezing solutions as ice forms and are being concentrated in water underneath the ice. Thompson and Nelson (1956) describe similar conditions.

Differences in the relative amounts of major ions among salt, water, and ice samples indicate that some ions are being concentrated more than others, suggesting a geochemical control on the levels of certain ions with progressive concentration through freezing. In the less saline conditions of wetland (18), SO_4 and Mg are increasing in pondwater at the expense of alkalinity, Ca, and Na. A similar trend is noted in the saline samples of wetland (20), except that differences between SO_4 and alkalinity are minor at these high concentrations. A model developed by Hardie and Eugster (1970) to explain the evolution of closed basin brines by evaporation predicts that with progressive concentration the relative amounts of alkalinity and Ca will decrease; however, in these solutions Na seems to be controlled also. An X-ray analysis of the salt collected on top of the ice indicated a dominance of mirabilite, epsomite, and gypsum ($CaSO_4 \cdot 2H_2O$) with smaller amounts of calcite ($CaCO_3$). Thenardite (Na_2SO_4) was essentially absent. Mirabilite and epsomite are common, extremely soluble Na and Mg sulfate salts and are not normally expected to exist in equilibrium with any but the most saline solutions.

Freezing, however, acts as a concentration mechanism active in saturated soils that removes water from solution and can cause even very soluble minerals to precipitate. At 30°C, epsomite and mirabilite have similar solubilities (Fig. 1). The solubility of each decreases with temperature. However, at 0°C mirabilite is one-fourth as soluble as epsomite. In sulfatic solutions where Na and Mg concentrations are high, mirabilite should precipitate before epsomite upon freezing. The salt collected from the surface ice is enriched in sodium, a further indication that mirabilite precipitation occurs prior to epsomite. Under conditions of extreme concentration of sulfatic solutions, mirabilite saturation may act to control the activity of Na in the same way that gypsum saturation controls Ca activity. This would allow the more soluble Mg-sulfates to accumulate in unfrozen water.

Freezing from the surface downward may concentrate dissolved solids at depth in a saturated soil and alter soil-solution composition in much the same way, affecting mineral precipitation and wetland soil morphology. Data from groundwater extractors in the shallow marsh of wetland (20) show an enrichment in magnesium over sodium with depth similar to that seen in the ice and pondwater samples. However, more data from these extractors is needed to show clearly that depth-dependent changes in soil-solution composition occurs because of freezing.

Table 1. Conductivity and Relative Ionic Composition* of Unfrozen Water, Ice, and Aeolian Salt from Wetlands 20 and 18.

Wetland #	Sample	EC dS/m	SO_4	Alk**	Ca	Mg	Na.
			---% Anions---		---% Cations---		
20	Fall	18.3	96.3	1.2	4.6	42.5	50.9
	Ice^1	11.1	95.8	2.6	6.8	40.5	51.4
	Ice^2	13.7	95.1	2.9	3.5	47.0	46.3
	Ice^3	8.0	93.5	4.7	4.4	46.3	47.7
	W inter^1	44.0	94.7	3.5	2.1	54.5	42.3
	W inter^2	61.9	95.4	2.5	1.5	59.7	37.3
	W inter^3	40.6	93.2	5.0	2.7	55.9	42.3
	Salt	-	96.5	2.6	8.6	26.1	64.5
18	Fall	2.6	62.4	30.5	19.9	36.1	40.8
	Winter	9.9	84.3	10.3	16.5	51.5	30.2

* mmol(+/-)L basis.
** Alkalinity (Alk.) includes HCO_3 and CO_3.

CONCLUSIONS

Sulfate minerals frequently contain waters of hydration in their crystal structure. The hydrogen bonds associated with these waters of hydration are exceedingly temperature dependent; therefore differential solubility of sulfate salts occurs in saline, high sulfate soils.

Mirabilite, dominant in salt released from the ice of the saline wetland, in particular changes solubility with temperature. Freezing concentrates the soil solution to levels that may result in mirabilite precipitation. The mineral precipitation sequence that occurs at or near freezing apparently can segregate ions in soil profiles. Because of their greater solubility magnesium minerals do not form until later in the freezing process. Thus Mg may be concentrated over Na in the soil solution or in pond water during freezing.

We hypothesize that in saline soils high in sulfate, top down freezing tends to maximize the sodic influence by removing magnesium; the result is that a natric or sodium affected soil can occur with lower amounts of sodium ions present than in an unfrozen soil or in a soil high in chloride salt where temperature dependent solubilities are not as important.

REFERENCES

Arndt, J.L. and J.L. Richardson. 1985. Winter effects on the salt balance of saline ponds in North Dakota. Proc. N.D. Acad. Sci., 36, p 54.

Arndt, J.L. and J.L. Richardson. 1988. Hydrology, salinity, and hydric soil development in a North Dakota prairie pothole wetland system. Wetlands: 8:94-108.

Arndt, J.L. and J.L. Richardson. 1989. Geochemical development of hydric soil salinity in a North Dakota prairie-pothole wetland system. Soil Sci. Soc. Am. J. 53:848-855.

Hardie, L.A. and H.P. Eugster. 1970. The evolution of closed-basin brines. Mineral. Soc. Am. Spec. Pap. 3:273-290.

Hendry, M.J., J.A. Cherry, and E.I. Wallick. 1986. Origin and distribution of sulfate in a fractured till in southern Alberta, Canada. Water Resour. Res. 22:45-61.

Keller, L.P., G.J. McCarthy, and J.L. Richardson. 1986a. Mineralogy and stability of soil evaporites in North Dakota. Soil Sci. Soc. Am. J. 50:1069-1071.

Keller, L.P., G.J. McCarthy, and J.L. Richardson. 1986b. Laboratory modeling of northern Great Plain salt efflorescence mineralogy. Soil Sci. Soc. Am. J. 50: 1362-1367.

Last, W.M. and T.H. Scheweyan. 1983. Sedimentology and geochemistry of saline lakes of the great plains. Hydrobiologia, 105, 245-263.

Soil Survey Staff. 1984. Procedures for collecting soil samples and methods of analysis for soil survey. USDA Soil Cons. Serv., Soil Survey Invest. Rpt. No. 1, U.S. Govt. Printing Office, Wash. D.C.

Thompson, T.G. and K.H. Nelson. 1956. Concentration of brines and deposition of salts from sea water under frigid conditions. Am. J. Sci., 254, 227-238.

Timpson , M.E. and J.L. Richardson. 1986. Ionic composition and distribution in saline seeps of southwestern North Dakota, USA. Geoderma 25:295-305.

Timpson, M.E., J.L. Richardson, L.D. Keller and G.J. McCarthy. 1986. Evaporite mineralogy associated with saline seeps in southwestern North Dakota. Soil Sci. Soc. Am. J., 50(2), in press.

Nitrogen Studies with Wheat under Zero and Conventional Tillage

R.J. Soper and M.R. Grenier
Department of Soil Science
University of Manitoba

INTRODUCTION

Zero tillage in North America is gaining in popularity due to its beneficial effects from decreased production costs, reduced soil erosion and improved soil moisture conditions. Successes with the new systems have varied among and within regions. In general, yields under zero tillage have been equal or somewhat higher compared to those under conventional tillage when good management practices have been used and continued for some time (Shea and Moschler, 1960; Moschler et al. 1972; Kitur et al. 1984; Van Doren et al. 1976; Legg et al. 1979; Dick and Van Doren, 1985; Rice et al. 1986; Elmore 1987; Edwards et al. 1988; Wagger and Denton 1989). Consistently lower yields on zero-tilled soils are most frequently attained on poorly drained, heavy-textured soils that are colder, wetter and less well aerated. (Unger and McCalla, 1980).

Dick and Van Doren (1985) in long-term studies have shown that no-till continuously cropped corn yielded better on well drained soil and lower on a poorly drained soil when compared to corn grown on a plowed soil. Yields were variable between the two systems of tillage on a soil of intermediate drainage. Yields of oat and soybean grown in rotation with corn on the same soils gave similar results. Griffith et al. (1973) had similar findings. Other researchers have found reduced yields with corn due to no-tillage on fine-textured, poorly drained soils. (Mock and Erbach 1977; Gebharat and Minor 1983; Wall and Stobbe 1983; Johnson and Lowery 1985; Al-Darby and Lowery 1986; Webber et al. 1987). Griffith et al. (1988) in Indiana, in long term studies, found that the organic matter content of the poorly drained soils was a factor in the lower yields. No-till corn yielded lower on a soil high in organic matter content while on a low organic matter soil the yields were higher than on a plowed soil.

Several short-term studies have shown that yields of crops under no-tillage may be lower than those under conventional tillage if zero or low amounts of N are added, yet equal or superior if large amounts of N are added (Triplett and Van Doren 1969; Moschler et al. 1972; Moschler and Martens 1975; Legg et al. 1979; Kitur et al. 1984; Meisinger et al. 1985; Fox and Piekielek 1987; Karlen and Gooden 1987). These studies suggest that soil N is less available for no-tillage crops; although other researchers have found that there is no difference in N uptake among tillage systems including no-tillage (Power et al. 1986; Levin et al. 1987; Locke and Hons 1988a, Locke and Hons 1988b; Halvorson and Hartman 1988). There are many reasons why soil N may be less available under no tillage viz. denitrification, leaching, less mineralization of soil organic N and N immobilization. Of these, lower N mineralization would most likely be the cause. Rice et al. (1986) in Kentucky showed, in a long term study with corn, that during the first nine years yields with zero N fertilizer were greater in conventional tillage than in no-tillage, but at high rates of N fertilizer the yields were similar. In subsequent years there were no differences between the tillage systems in yield with and without added N. The authors suggested that after some time soils under no-tillage will reach equilibrium levels of soil organic N such that they can mineralize as much N as tilled soils even though the percentage of breakdown of the organic N in the tilled soils remains greater. This suggestion is supported by numerous studies which have shown that soils under conventional tillage have less organic matter and organic N than no-tillage soils (Moschler et al. 1972; Lal 1976; Blevins et al. 1977; Blevins et al. 1983; Dick 1983; Lamb et al. 1985; Gallaher and Ferrer 1987).

In spite of occurrences of less available soil N under no-tillage systems, several studies have shown that fertilizer N is at least as available in no-tillage soils as in conventionally tilled soils (Moschler et al 1972; Moschler and Martens, 1974; Fox and Piekielek 1977; Legg et al. 1979).

Numerous studies have found that no-tillage cropping results in lower soil pH valves than does conventional tillage (Shear and Moschler 1969; Moschler et al. 1973; Blevins et al. 1977; Blevins 1978; Blevins et al. 1983; Dick 1983; Dalal 1989). The effect is most evident in the 0-5 cm depths of soils, but extends beyond this layer and in some cases to depths of 20 and 30 cm. The increase in acidity was greatly enhanced by increasing the amount of N, acid-forming fertilizers added. Additions of lime were necessary in some soils to achieve maximum production; more lime was required for the no-tillage soils (Shear and Moschler 1969; Moschler et al. 1973; Blevins et al. 1978; Dick 1983; Dalal 1989). Blevins et al. (1977) found that exchangeable Al was less than expected in the surface of the no-tillage soils and suggested from the research of Thomas (1975) that the higher organic matter in the surface larger suppressed exchangeable Al and lessened any toxic effects.

This study was part of a project designed to study methods of soil management and fertilizer use which could be used to overcome the inherent physical and chemical properties which limit crop yields on sandy soils. The major thrust of the project was on zero tillage as a management practice to reduce or eliminate soil erosion. The study evaluates the effects of zero tillage on wheat yields, response to N fertilizer, soil N mineralization, N balance and soil pH.

MATERIALS AND METHODS

The soils on which the sites were located are series of the Almasippi Association. The Almasippi Association is characterized by a sandy surface layer with underlying fine textured lacustrine deposits. Thee Willowcrest series are located in the middle positions of gentle slopes of undulating landscape, are relatively well drained, non-calcareous and classified as Gleyed Orthic Black Chernozems. The site was located near St. Claude. The surface 15 cm had a pH of 7.0, conductivity of 0.15 dSm^{-1}, and an organic matter content of 2.6 percent. The Almasippi series are located in the lower slope positions. The Almasippi series soils are imperfectly drained, calcareous and classified as Gleyed Rego Black Chernozems. The site was located near Haywood. The surface 15 cm had a pH of 7.8, conductivity of 0.38 dSm^{-1} and an organic matter content of 3.4 percent.

In order to study the effiency ofnitrogen fertilizer use under zero-and conventional-tillage, an experiment at two locations consisting of zero-tillage treatments and conventional tillage treatments was conducted. Ideally, for the purpose of statistical analysis, zero- and conventional tillage treatments should have been completely randomized with one another. However, due to physical constraints imposed by the tillage machinery, the two tillage methods were separated into two independent blocks. Within each tillage method, a randomized complete block design, consisting of seven fertilizer treatments and four replicates, was conducted. Treatment plots measured four metres in width and eight metres in length. Each treatment plot contained 20 seed rows of 20 cm metres. The total dimensions of each tillage method block were 28 metres by 32 metres.

In the spring of each study year, nitrogen was hand broadcast as ammonium nitrate at rates of 0, 30, 60, 90, 120, 180 and 240 Kg N ha^{-1}. In each year these treatments were superimposed on the previous years' treatment. For conventional tillage treatments, nitrogen and crop residues were incorporated to a depth of 15 cm using a rotovator immediately following fertilizer application. For zero-tillage treatments all crop residues were left undisturbed on the surface except for the disturbance caused by a seed drill.

All plots were seeded to wheat (Triticum aestivum var. Columbus) at a rate of 100 Kg ha^{-1} using a Versatile 200 Zero-Till drill. Phosphorous and potassium were placed with the seed at rates of 17 kg P ha^{-1} as 0-46-0 and 33 kg K ha^{-1} as 0-0-60. Weed control throughout the growing season was accomplished through the use of chemical herbicides.

At each site the wheat crop was sampled at the soft dough stage of filling (data not given) and at maturity to determine yield and nutrient content. At each harvest date the above ground-plant samples were taken from five central rows, measuring one metre in length, within each nitrogen treatment plot. At the first harvest, whole plant samples were dried and ground to pass through a 2 mm sieve. At final harvest, plant samples were dried, separated into seed and straw components and were ground to pass through a 2 mm sieve. Total nitrogen content of plant material was determined by a modified Kjeldahl-Gunning method as described by Jackson (1958). Nitrogen content was determined using a Tecator Kjeltec Auto 1030 Analyzer.

Unfortunately, in 1985, the nitrogen study crop at Haywood was severely damaged by grasshoppers despite repeated attempts at chemical control. In 1986, this study was reestablished on a site immediately adjacent to the original site.

In each of the study years beginning in 1986, soil samples were taken in the early spring prior to seeding and in the late fall subsequent to final harvest. Soils were sampled at depths of 0-15cm, 15-30cm, 30-60cm, 60-90cm and 90-120cm from the center of each nitrogen treatment plot and analyzed for nitrate-nitrogen content. Soil nitrate nitrogen for 1985-86 soil samples was determined by a phenoldisulphonic method described by Bremner (1965), and for 1987-88 samples nitrate nitrogen was determined by a modified Greiss-Ilosvay method described by Keeney and Nelson (1982). Nitrate nitrogen was determined using a FIAstar 5020 analyzer.

To determine the impact of four years of applying various nitrogen rates on soil pH at the St. Claude site, each of the nitrogen treatments were soil sampled, at harvest time 1988, at shallow depths of 0-5cm, 5-10cm, 10-20cm, 20-30cm, and deeper depths of 30-60cm, 60-90cm and 90-120cm. Soil pH was determined in a soil:water (1:2) mixture for each depth sampled.

The apparent amount of soil N mineralized from the spring of 1986 to the fall of 1988 for 0, 30 and 60 Kg nitrogen subplot treatments under both conventional and zero-tillage at each site was calculated. Nitrogen mineralized during the growing season was calculated by the use of the equation:

Amount of N mineralized = FNO_3-N + Grain-N + Immob-N - Fert-N - SNO_3-N

where the amount of N mineralized is expressed in kg ha^{-1}, FNO_3 is fall nitrate-N to 120 cm in kg ha^{-1} , Grain-N is total N accumulation in the grain, Immob-N is an estimate of the amount of N immobilized by the straw and roots, Fert-N is the amount of nitrogen added as fertilizer and SNO_3 is spring NO_3-N to 120 cm in kg ha^{-1}. Nitrogen mineralized over winter was calculated by use of the equation:

Amount N mineralized over winter = SNO_3 - FNO_3

where again SNO_3 AND FNO_3 are spring and fall nitrate-N levels to 120 cm in kg ha^{-1}. Losses of nitrate-N due to leaching and denitrification were not taken in account. Nitrogen from other sources (rainfall etc.) was also not included.

A nitrogen balance sheet for the period starting in the spring of 1986 to the fall of 1988 was calculated using the following equation:

Total inputs = Initial NO_3-N + N added + N mineralized

where Initial NO_3-N is the NO_3-N to a depth of 120 cm in the spring of 1986, N added is the total amount of N added from 1986 to 1988 and N mineralized is an estimate of the nitrogen mineralized from 1986 to 1988 for the 0 nitrogen treatment. Total inputs were calculated using the equation:

Total outputs = Grain N + N immobilized + final NO_3-N

where Grain N represents the amount of N removed in the grain of wheat for 1986 to 1988, N immobilized is an estimate of the amount of N immobilized by the wheat residue, and final NO_3-N is the NO_3-N to a depth of 120 cm in the fall of 1988. The difference between total inputs and outputs represents the amount of nitrogen for which we could not account.

RESULTS AND DISCUSSION

Grain yields for the two sites averaged over the years 1986 to 1988 are given in Table 1. The yields at the Almasippi site are somewhat lower than those for the Willowcrest site. Part of these differences may be explained by a later seeding date at the Almasippi site in two of the three years due to wet conditions. Responses in yield to N were similar for the two sites and tillage systems. It would appear that 60 kg ha^{-1} of added N would suffice for economic yields. The tillage treatments had no effect on yield; the average difference between them for the two sites for the three years was 0.3 percent. These results suggest that there is no penalty to be paid for zero tillage with regard to yield of wheat. One might even speculate that in years when there is severe wind erosion the yield for zero-tillage soils might well be higher than those with conventional tillage.

Nitrogen uptake data are presented in Table 2. In general N uptake increased with increasing amounts of added N, but seemed to level off at 120 to 180 kg N ha^{-1}. The effect of tillage appears to be small, however, there is a trend towards less N uptake in the zero-tillage treatments for the zero and 30 kg ha^{-1} N addition at the Almasippi site and the zero N treatment for the Willowcrest site. These results are in agreement with Rice et al. (1986) who showed that no-tillage systems in the short term mineralized less organic N than conventional-tillage systems.

Nitrogen mineralized from the spring of 1986 to the fall of 1988 for three nitrogen treatments under tillage and zero-tillage wheat were calculated for both sites and are reported in Table 3. At the Willowcrest site the amount of nitrogen mineralized averaged 307 kg ha^{-1} and ranged from 238 to 349 under conventional tillage and averaged 333 kg ha^{-1} and ranged from 256 to 371 kg ha^{-1} under zero tillage. These values indicate that there was little difference in the amount of N mineralized due to tillage practices. Variability in the amount of N mineralized may be due to losses of nitrate-N by leaching and denitrification which were not accounted for. At the Almasippi site there was much less variability in the amount of N mineralized for the nitrogen treatments. The amount of N mineralized averaged 395 and 298 kg ha^{-1} under conventional and zero-tillage respectively. These values indicate that tillage did affect the amount of N mineralized and that decomposition of organic matter or mineralization of N was greater under conventional tillage.

Averaging N mineralization over both sites we find that the amount of N mineralized was 351 and 316 kg ha^{-1} under conventional and zero tillage respectively. Converting these values to yearly or annual mineralization rates, we find that the amount of N mineralized was 117 and 105 kg ha^{-1} $year^{-1}$ under tillage and zero-tillage respectively. Expressing these annual mineralization rates in terms of the total N content of these soils to 30 cm result in decomposition rates of 1.82 and 1.64 percent under tillage and zero-tillage respectively. Considering these annual mineralization rates in terms of the total N content of these soils to only the surface 15 cm result in decomposition rates of 3.13 and 2.80 percent under tillage and zero-tillage respectively. Thus decomposition is greater under tillage than under zero-tillage. Therefore, these zero-tilled sandy soils should eventually have more soil organic N and soil organic matter than if they were tilled. This contention is supported by numerous studies (Moschler et al. 1972; Lal 1976; Blevins et al. 1977; Blevins et al. 1983; Dick 1983; Lamb et al. 1985; Gallaher and Ferrer 1987). However, under both tillage systems the organic matter content of these soils should decline with time.

An approximate N balance for the sites from 1986 to 1988 is shown in Table 4. The total inputs represents NO_3-N is the spring of 1986, a calculated N mineralization from spring 1986 to harvest time 1988 for the zero N treatment and the N added as fertilizer. Total outputs represents grain nitrogen, N immobilized in straw plus roots, and NO_3-N in the fall of 1988. The figures in Table 4 are an average of the seven fertilizer treatments. The results indicate that N unaccounted for was small, ranging from 6 to 15 percent and that the apparent losses were greater for the tilled soil than for the zero-tilled soils. This might indicate that N fertilizer efficiency was greater for zero-tillage which is in agreement with other studies. (Moschler et al. 1972; Moschler and Martens 1975; Legg et al. 1979).

To determine the impact of four years of nitrogen fertilization on soil acidity, soil pH was measured at depth intervals to 30 cm. Soil pH was strongly influenced by both tillage and N treatments (Fig. 1). Under conventional tillage there were slight decreases in soil pH values for the 0-5 and 5-10 cm depths from nitrogen additions ranging from 0 to 120 kg N h^{-1}. The higher N additions resulted in sharp decreases for both depths. Under zero tillage the change in soil pH seemed to be limited to the surface, 0-5 cm, layer, although a slight dip occurred in the 5-10 cm depth at the higher N additions. The decrease in pH of the 0-5 cm depth was slight for additions of N up to 120 kg N ha^{-1}, but much greater for the higher rates. Soil pH for 0-5 cm depth ranged from 6.83 to 5.63 and 6.85 to 5.39 with increasing N additions under conventional and zero tillage respectively. There was more total acidity in the zero tilled soils than in conventionally tilled soils as measured by H ions in solution to a depth of 30 cm. There was no or little effect of tillage or nitrogen treatment on soil pH values for depths below 10 cm.

SUMMARY

Tillage treatments had no effect on wheat yields or response of wheat to added N. There was evidence that soil N was less available under zero tillage than under conventional tillage because of lower soil N mineralization. Nitrogen balance sheets indicated that losses of N were higher under conventional tillage than under zero tillage. Soil acidification from N fertilizer was less when the soils were tilled.

ACKNOWLEDGEMENT

Financial assistance from ERDAF, Agriculture Canada is gratefully acknowledged.

Table 1. Effect of N additions and tillage on grain yields (kg ha^{-1}) average for 1986-1988.

	WILLOWCREST		ALMASIPPI	
N added kg ha^{-1}	Zero Tillage	Tillage	Zero Tillage	Tillage
0	1635	1677	1762	1789
30	1813	1807	1664	1651
60	2138	2213	2045	1823
90	2126	2102	1678	1760
120	2231	2335	1801	1658
180	2483	2306	2179	2167
240	2210	2395	1829	1833
Mean	2091	2119	1851	1812

Table 2. Effect of N additions and tillage on N uptake by wheat (grain + straw) kg ha^{-1} for 1986-1988.

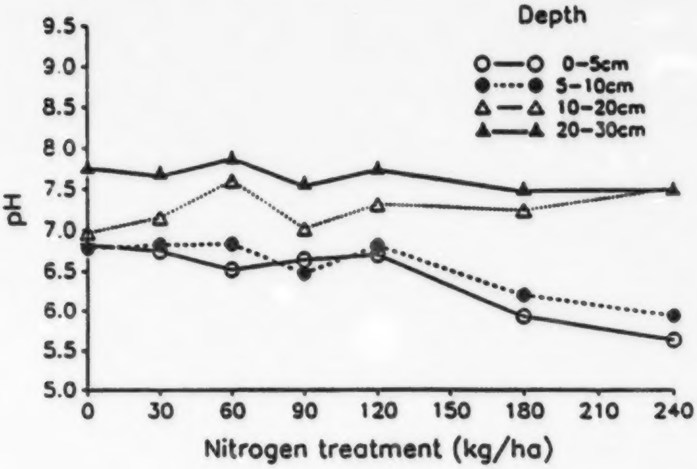
	WILLOWCREST		ALMASIPPI	
N added kg ha^{-1}	Zero Tillage	Tillage	Zero Tillage	Tillage
0	55	63	66	80
30	64	65	68	80
60	80	82	90	91
90	94	92	80	89
120	103	108	90	91
180	115	112	98	105
240	109	111	94	95
Mean	89	90	84	90

Table 3. Mineralization of organic nitrogen from May 1986 to August 1988 in kg NO_3-N per ha to 120 cm

Location	N added kg ha^{-1}	Tillage	Zero Tillage
WILLOWCREST	0	349	371
	30	238	372
	60	334	256
	Mean	307	333
ALMASIPPI			
	0	397	316
	30	399	280
	60	388	297
	Mean	395	298
Mean of sites		351	316
Yearly Mineralization		117	105
Organic N (0-30 cm)			
Decomposition rate		1.82%	1.64%

Table 4. Nitrogen balance sheet for the period spring 1986 to fall 1988.

	kg N ha-1				
	Total Inputs	Total-Outputs	Input-Outputs	Unaccounted for%	Accounted for %
WILLOWCREST					
Zero Tillage	790	709	81	10	90
Tillage	768	652	116	15	85
ALMASIPPI					
Zero Tillage	797	749	48	6	94
Tillage	878	755	123	14	86


Conventional Tillage

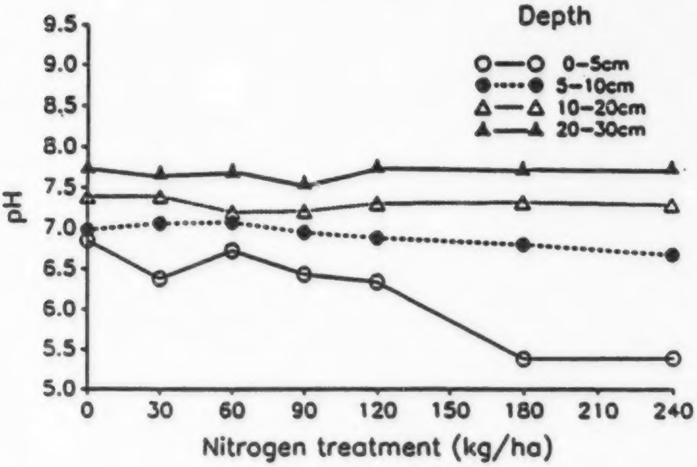

Zero Tillage

Fig. 1 Change in soil pH at various depths due to nitrogen and tillage treatments.

LITERATURE CITED

Al-Darby, A.M. and Lowey, B. 1986. Evaluation of corn growth and productivity with three conservation tillage systems. Agron. J. 78:901-907.

Bremner, J.M. 1965. Inorganic form of nitrogen. In C.A. Black et al. (ed). Methods of soil analysis, Part 2. Agronomy 9:1179-1237. Am. Soc. of Agron., Inc. Madison, Wis.

Blevins, R.L. Thomas, G.W. and Cornelius, P.L. 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. Agron. J. 69:383-386.

Blevins, R.L., Murdock, L.W. and Thomas, G.W. 1978. Effect of lime application on no-tillage and conventionally tilled corn. Agron. J. 70:329-326.

Blevins, R.L., Thomas, G.W., Smith, M.S., Frye, W.W. and Cornelius, P.L. 1983. Changes in soil properties after 10 year continuous non-tilled and conventionally tilled corn. Soil Tillage Res. 3:135-146.

Carter, M.R., and Rennie, D.A., 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can J. Soil Sci. 62: 587-597.

Dalal, R.C. 1989. Long term effects of no-tillage, crop residue, and nitrogen application on properties of a Vertisol. Soil Sci. Soc. Am. J. 53:1511-1515.

Dick, W.A. 1983. Organic carbon, nitrogen and phosphorus concentrations, and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47:102-107.

Dick, W.A. and Van Doren, D.M., Jr., 1985. Continuous tillage and rotation combination effects on corn, soybean, and oat yields. Agron. J. 77:459-465.

Edwards, J.H., Thurlon, D.L., and Eason, J.T. 1988. Influence of tillage and crop rotation on yields of corn, soybeans, and wheat. Agron. J. 80:76-80.

Elmore, R.W. 1987. Soybean cultivar response to tillage system. Agron. J. 79:114-118.

Fox, R.H., and Piekielek, W.P. 1987. Yield response to N fertilizer and N fertilizer use efficiency in no-tillage and plow-tillage corn. Commun. Soil Sci. Plant Anal. 18:495-513.

Gallaher, R.N. and Ferrer, M.B. 1987. Effect of no-tillage vs. conventional tillage on soil organic matter and nitrogen contents. Commun. Soil Sci. Plant Anal. 18:1061-1076.

Gebharat, N.R., and Minor, H.C., 1983. Soybean production systems for claypan soils. Agron. J. 75:532-537.

Griffith, D.R., Mannering, J.V., Galloway, H.M., Parsons, S.D. and Richey, C.B. 1973. Effect of eight tillage-planting systems on soil temperature, plant stand, plant growth and yield of corn on five Indiana soils. Agron. J. 65:321-326.

Griffith, D.R., Kladivko, E.J., Mannering, J.V., West, T.D. and Parsons, S.D., 1988. Long-term tillage and rotation effects on corn growth and yield on high and low organic matter, poorly drained soils. Agron. J. 80:599-605.

Halvorson, A.D. and Hartman, G.P. 1988. Nitrogen needs of sugarbeet produced with reduced-tillage systems. Agron. J. 80:719-722.

Jackson, M.L., 1958. Soil chemical analysis. Prentice-Hall, Inc., Englewood Cliffs, N.J. Sixth printing, 1970, by the author, Dept. of Soil Science, Univ. of Wisconsin, Madison.

Johnston, M.D., and Lowery, B. 1985. Effect of three conservation tillage practices on soil temperature and thermal properties. Soil Sci. Soc. Am. J.49:1547-1552.

Karlen, D.L. and Gooden, D.T. 1987. Tillage systems for wheat production in the Southeastern Coastal Plains. Agron. J. 79:582-587.

Keeney, D.R. and Nelson, D.W. 1982. In A.L. Page et al. (ed.). Methods of soil analysis, Part 2, 2nd edition. pp.643-698. American Society of Agronomy, Madison, WI.

Kitur, B.K., Smith, M.S., Blevins, R.L. and Frye, W.W. 1984. Fate of ^{15} N depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron. J. 76:240-242.

Lal, R. 1976. No-tillage effects on soil properties under different crops in Western Nigeria. Soil Sci. Soc. Am. J. 40:762-768.

Lamb, J.A., Peterson, G.A. and Fenster, C.R. 1985. Wheat fallow tillage systems' effect on a newly cultivated grassland soils' nitrogen budget. Soil Sci. Soc. Am. J. 49:352-356.

Legg, J.O., Stanford, G., Bennett, O.L. 1979. Utilization of labelled N fertilizer by silage corn under conventional and no-till culture. Agron. J. 71:1009-1015.

Levin, A., Beegle, D.B. and Fox, R.H. 1987. Effect of tillage on residual nitrogen availability from alfalfa to succeeding corn crops. Agron. J. 79:34-38.

Locke, M.A., and Hons, F.M. 1988a. Tillage effect on seasonal accumulation of labelled fertilizer nitrogen in sorghum. Crop Science Soc. Am. 28:694-700.

Locke, M.A., and Hons, F.M. 1988b. Fertilizer placement effects on seasonal nitrogen accumulation and yield of no-tillage and conventional tillage sorghum. Agron. J. 80:180-185.

Meisinger, J.J., Bandel, V.A., Stanford, G., Legg, J.O. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage I. Four year results using labelled N fertilizer on an Atlantic Coastal Plain soil. Agron. J. 77:602-611.

Mock, J.J. and Erbach, D.C. 1977. Influence of conservation tillage environments on growth and productivity of corn. Agron. J. 69:337-340.

Moschler, W.W., Shear, G.N., Martens, D.C., Jones, G.D. and Wilmouth, R.R. 1972. Comparative yield and fertilizer efficiency of no-tillage and conventionally tilled corn. Agron. J. 64:229-231.

Moschler, W.W., Martens, D.C., Rich, C.I. and Shear, G.M. 1973. Comparative lime effects on continuous no-tillage and conventional tilled corn. Agron. J., 65:781-783.

Moschler, W.W., Martens, D.C. and Shear, G.M., 1975. Residual fertility in soil continuously field cropped to corn by conventional and no-tillage methods. Agron. J. 67:45-48.

Moschler, W.W., and Martens, D.C., 1975. Nitrogen, phosphorus and potassium requirements in no-tillage and conventional tillage corn. Soil Sci. Soc. Am. Proc. 39;886-891.

Power, J.F., Wilhelm, W.W. and Doran, J.W. 1986. Recovery of fertilizer nitrogen by wheat as affected by fallow method. Soil Sci. Soc. Am. J. 50:1499-1503.

Rice, C.W., Smith, M.S. and Blevins, R.L. 1986. Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production. Soil Sci. Soc. Am. J. 50:1206-1210.

Shear, G.N. and Moschler, W.W. 1969. Continuous corn by the no-tillage and conventional tilled methods. Agron. J. 61:524-526.

Thomas, G.W., 1975. The relationship between organic matter content and exchangeable aluminium in acid soil. Soil Sci. Soc. Am. Proc. 39:591.

Triplett, G.B., Jr. and Van Doren, D.M, Jr. 1969. Nitrogen, phosphorus and potassium fertilizer of non-tilled maize. Agron. J. 61:637-639.

Unger, P.W. and McCalla, T.M. 1980. Conservation tillage systems. Adv. Agron. 33:1-58.

Wagger, M.G. and Denton, M.G. 1989. Tillage effects on grain yields in a wheat, double-crop soybean and corn rotation. Agron. J. 81:493-498.

Wall, D.A. and Stobbe, E.H. 1983. The response of eight corn (Zea mays h.) hybrides to zero tillage in Manitoba. Can. J. Plant Sci. 63:753-757.

Webber, C.L., III, Gebhardt, M.R. and Kern, H.D. 1987. Effect of tillage on soybean growth and seed production. Agron. J. 79:952-956.

Van Doren, D.M., Jr., Triplett, G.B., and Henry, J.E. 1976. Influence of long-term tillage, crop rotation, and soil type combinations on corn yield. Soil Sci. Soc. Am. J. 40:100-105.

Report of the East Central Saskatchewan Soil Conservation Project

Grant J. McCallum
Conservation Agronomist
A. G. Kuziak Building
Yorkton, Sask.
S3N 2Y4

The East Central Saskatchewan Soil Conservation Project is a four year research and demonstration project designed to investigate:

1) the profitability of extended crop rotations
2) the value of reduced or conservation tillage

The key to this project is a three tiered program consisting of:

1) three research sites which examine grain and oilseed production under zero tillage, minimum tillage, and conventional tillage, using continuous cropping and a 50/50 crop fallow rotation. All crop and soil parameters are being monitored, and all inputs are being recorded so that a complete economic analysis can be made.

2) one demonstration site in each of the eight agricultural extension districts that form the region. Each site was planned in co-operation with the local extension agrologist and district extension board. Their purpose is to illustrate a practical field scale example of soil conservation that is of interest or concern to local producers.

3) a major extension effort to promote project results and conservation practices through various technology transfer methods associated with the agriculture industry.

Although soil and climatic conditions in this region are suitable for extended cropping, a large number of producers still employ a 50/50 crop-fallow rotation, leading to an excessive amount of tillage. No soil conservation research has ever been conducted in this area and for this reason the project was established in this location.

This project involves three sponsoring groups:

1) Saskatchewan Agriculture:
Project demonstration sites are co-ordinated in consultation with the local agricultural extension districts. Extension activities such as tours, seminars, and field days are planned with the extension agrologists.

2) Agriculture Canada:
Two research agronomists from the Indian Head Experimental Farm oversee the research component of the project. They assist with all field operations, data collection, and analysis. Agriculture Canada

has also provided the use of plot equipment and a considerable amount of shop time and labour for equipment preparation and maintenance.

3) Hoechst Canada Inc.:
Hoechst has contributed technical assistance to develop and promote all levels of the field and extension programs. As well, Hoechst has provided capital funding for the purchase of research equipment and supplies.

The majority of the funding for the project is provided through the Federal-Provincial Agricultural Development Agreement, ERDA. The remainder of the funding is provided by Hoechst Canada Inc., Agriculture Division.

The project receives direction from a steering committee which is comprised of individuals from the three sponsoring groups, and four farmer members chosen from the various agriculture extension districts of East Central Saskatchewan.

Summary of Results

Research Project:

The research portion of this project has two objectives. The first objective is to investigate conservation tillage practices that minimize the effects of soil erosion. The second objective is to investigate extended cropping as a method of alleviating the process of soil degradation by the practice of summerfallowing. The intent is to document in as much detail as possible, how tillage systems and cropping systems affect soil water, plant growth, weed populations and control, final grain yield, and economic returns.

The practice of summerfallowing results in the accumulation of nitrate nitrogen through the process of mineralization. Given this fact, proper soil fertility and soil moisture management should alleviate the need for summerfallowing. Available soil moisture was determined just prior to seeding each spring and immediately after harvest each fall, at 30 cm increments to a depth of 120 cm. Data was recorded for each tillage system, cropping rotation, and crop. Total available soil moisture, fallow moisture recharge, and stubble/fallow variations were determined each year. Growing season precipitation was monitored with a CR21 Micrologger and tipping bucket to provide data for calculating water use efficiency.

Soil temperature was recorded daily by a CR21 Micrologger. Thermistor probes were placed at 10 cm and 40 cm in zero till and conventional till plots to determine tillage related temperature variations and soil moisture/temperature interactions.

Weeds were counted and categorized by weed type for each tillage system, cropping rotation, and crop, to determine shifts in weed spectrum and/or density. The weed survey methodology developed by Dr. Gord Thomas, Agriculture Canada, was utilized in these determinations.

Plants/square meter, plant height, heads/square meter, and thousand kernel weight were calculated for each tillage system, cropping rotation, and crop.

Yields were determined for each tillage system, cropping rotation, and crop. Inputs and expenses were recorded to provide data for determining net returns and net expenditure for each treatment.

Soil Moisture:

One of the arguments used to justify the practice of summerfallowing is increased soil moisture content after the fallow period. Fallowing in Ituna and Waldron from 1987 to 1988 resulted in savings of only 2.2 cm and 2.9 cm of water respectively. These amounts of moisture could also have easily been saved in a continuous cropping situation with proper snow trapping and soil water conservation techniques.

Table 1 shows the total soil moisture recharge after the first and second winter at Ituna in 1988 and 1989 in the 0-120 cm layer on fallow plots.

Table 1 **Total soil moisture (cm) in the 0-120 cm soil layer on the fallow plots after the first and second winter of recharge for three tillage systems at Ituna.**

Tillage System	Soil Water (cm)		
	1988	1989	
Zero till	21.0	25.7	- 5.3
Minimum till	33.7	26.6	- 7.1
Convention till	30.1	24.7	- 5.4
Mean	31.6	25.7	

Table 2 gives a comparison of soil moisture conditions under fallow and stubble in the 0 - 120 cm soil layer for 1987, 1988 and 1989. The spring soil moisture conditions were lowest in 1989 for fallow and stubble when compared to 1987 and 1988. Over the three year period, minimum tillage fallow and stubble plots had the highest spring soil moisture content. Fallow moisture conditions have been greater than stubble, for all tillage systems.

Table 2 A comparison of soil moisture conditions for the 0-120 cm soil layer between 1987, 1988 and 1989 at Ituna.

Tillage System	Cropping System							
	Continuous				50/50			
	1987	1988	1989	Mean	1987	1988	1989	Mean
Zero till	25.1	28.7	21.6	25.1	27.6	31.4	25.7	28.2
Minimum till	27.2	31.1	23.8	27.4	32.8	33.2	26.6	30.9
Conventional till	25.7	31.0	20.9	25.9	30.6	34.9	24.7	30.1
Mean	26.0	30.3	22.1		30.3	33.2	25.7	

Tillage systems had no significant effect on total soil water in the 0-120 cm soil layer at Ebenezer (Table 3). However, the zero and minimum till plots tended to have more soil water than the conventional till plots. The fallow plots had 0.9 cm more water than stubble treatments.

Table 3 The overall effects of tillage and cropping systems on total soil water (cm) in the 0-120 cm soil layer after three years at Ebenezer (1987-1989)

Tillage System	Cropping System		
	Continuous	50/50	MEAN
Zero till	33.1	33.6	33.3
Minimum till	31.3	33.0	32.2
Conventional till	28.9	31.9	30.4
Mean[1]	31.9	32.8	

[1] The effects due to tillage and cropping systems were not significant. There was a significant tillage X cropping system interaction (pr = 0.017)

Table 4 shows similar effects from 1987 - 1989 in Waldron regarding soil moisture associated with tillage and cropping systems.

Table 4 The overall effects of tillage and cropping systems on total soil water (cm) in the 0-120 cm soil layer after three years at Waldron (1987 - 1989)

Tillage System	Cropping System[1]		
	Continuous	50/50	Mean
Zero till	26.4	29.0	27.7
Minimum till	24.4	27.5	25.9
Conventional till	21.5	25.6	23.6
Mean[2]	24.1	27.4	

[1] Orthogonal Contrast
Zero and Minimum Till vs. Conventional Till $p = 0.05$
Zero versus Minimum Till $p > 0.05$

[2] Significant cropping systems effect Pr = 0.0001

Weed Populations:

Table 5 shows a weed density comparison by weed type at Ituna in 1989 in # plants/sq. m.

There is very little variation in weed type densities between tillage systems except for annual broadleaf weeds, where the density in zero till plots is higher than in minimum and conventional till plots.

Table 5 Ituna 1989 Weed Type Comparison by Tillage System

Weed Type	Treatment Density (#/sq. m)		
	Zero Till	Minimum Till	Conventional Till
Annual Broad-leaved Weeds	14.4	6.4	5.4
Perennial Weeds	1.6	2.3	2.3
Volunteer Crop Weeds	5.2	2.1	0.5
Annual Grass Weeds	1.0	0.8	0.8
Winter Annual Weeds	1.0	0.1	0.2

When the density of weed types at Waldron is broken down according to tillage systems (Table 6), the density of weeds has remained the same for the zero and minimum tillage systems, but has increased for the conventional tillage system. Most of the increase under the conventional tillage system can be attributed to green foxtail infestations.

Table 6 **The effects of tillage systems on weed type densities (# of weeds per meter square) at Waldron after three years.**

Weed Type	Zero till				Minimum till				Conventional till			
	1986	1987	1988	1989	1986	1987	1988	1989	1986	1987	1988	1989
Annual grass	3.0	9.7	7.4	11.5	1.8	7.3	9.0	17.3	2.3	4.8	17.3	49.6
Annual Broad-leaved	9.0	20.8	18.2	8.8	10.0	16.6	13.8	7.0	7.7	19.4	17.0	7.31
Winter Annuals	0.1	0.0	1.3	0.2	0.0	0.0	1.2	0.2	0.0	1.0	2.5	0.5
Perennial weeds	7.9	0.3	3.6	3.9	9.0	17.9	7.0	5.1	7.1	2.1	4.4	1.7
Volunteer crops	0.7	0.4	0.0	5.3	0.0	1.7	0.3	2.8	0.0	2.8	0.3	0.9
Total	20.7	31.2	30.5	29.7	20.8	43.5	31.3	32.4	17.1	30.1	41.5	59.8

Economics:

A combined economic analysis was done taking all expenses and returns into consideration from 1987 - 1989 on a per acre basis.

Table 7.1 **The effects of tillage and cropping systems on yield (bu./ac.) and net return ($/ac.) of Katepwa Wheat after 3 years (1987 - 89), Westar Canola and HY320 after 2 years (1987 - 88), and Harrington Barley and Norlin Flax after 1 year of data (1989) at Waldron.**

Crop	Tillage System	Cropping System C - Continuous F - 50/50	Yield (bu./ac.)	Net Return ($/ac.)
Katepwa	Zero	C	22.46	6.33
		F	28.33	-4.06
	Minimum	C	17.64	-2.74
		F	24.82	-3.78

Table 7.1 (continued)

	Conventional	C	18.98	3.66
		F	25.62	16.53
HY320	Zero	C	30.30	-5.92
		F	29.50	-43.35
	Minimum	C	25.88	-4.80
		F	25.20	2.37
	Conventional	C	25.76	-7.13
		F	29.25	-12.20
Westar Canola	Zero	C	15.06	-12.13
		F	20.37	-6.07
	Minimum	C	14.42	-10.66
		F	17.86	-13.97
	Conventional	C	16.75	15.64
		F	20.22	26.31
Harrington Barley	Zero	C	43.24	-12.69
		F	67.85	5.62
	Minimum	C	32.71	-27.81
		F	58.35	6.95
	Conventional	C	27.91	-29.85
		F	54.86	10.72
Norlin Flax	Zero	C	16.84	65.36
		F	19.68	65.78
	Minimum	C	13.16	35.11
		F	15.38	44.34
	Conventional	C	11.24	26.03
		F	14.29	43.78

Table 7.2 The effects of tillage and cropping systems on yield (bu./ac.) and net return ($/ac.) of Katepwa Wheat after 3 years (1987-89), Westar Canola and HY320 after 2 years (1987 -88), and Harrington Barley and Norlin Flax after 1 year of data (1989) at Ituna.

Crop	Tillage System	Cropping System C - Continuous F - 50/50	Yield (bu./ac.)	Net Return ($/ac.)
Katepwa	Zero	C	24.4	-5.32
		F	32.0	1.07
	Minimum	C	24.70	15.63
		F	33.40	23.05
	Conventional	C	28.30	29.88
		F	31.40	28.01
HY320	Zero	C	33.91	-6.61
		F	36.27	-25.71
	Minimum	C	32.52	-0.74
		F	40.79	-5.82
	Conventional	C	34.91	4.42
		F	36.02	-5.33
Westar Canola	Zero	C	19.10	35.85
		F	20.30	16.89
	Minimum	C	17.58	35.95
		F	23.04	35.87
	Conventional	C	20.10	51.33
		F	22.97	52.00
Harrington Barley	Zero	C	35.90	-18.08
		F	52.48	-40.02
	Minimum	C	34.66	-11.32
		F	52.55	-8.73
	Conventional	C	44.69	0.11
		F	53.17	6.30
Norlin Flax	Zero	C	10.49	11.49
		F	11.54	-31.95
	Minimum	C	10.19	17.76
		F	13.52	14.39
	Conventional	C	11.84	34.29
		F	11.03	13.82

Growing conditions in 1988 and 1989 affected crop yields at both locations. Rainfall amounts were not substantial enough to offset the adverse effects of the period of heat stress experienced during both growing seasons.

Demonstration Project:

One demonstration project has been established in each of the eight agricultural extension districts that make up the East Central Region. These are field scale farmer co-operator sites that are planned in co-operation with the local extension agrologist and district extension board. The objectives are to illustrate some practical aspect of soil conservation in each district that is of interest or concern to local producers. 1989 is the fourth and final year of data collection from these sites.

Results from the demonstration projects are not analyzed by statistical procedures. For that reason, the material is not presented here. A summary of the results from the demonstration projects is available in the annual report.

A full copy of the Annual Report for the East Central Saskatchewan Soil Conservation Project is available by calling or writing to:

East Central Saskatchewan Soil Conservation Project
c/o Grant J. McCallum
A. G. Kuziak Building
72 Smith Street East
Yorkton, Sask
S3N 2Y4
Phone # (306) 786-1504
Fax # (306) 786-1511

SPRIGGING RHIZOMATOUS GRASSES IN SALINE-ALKALINE SOILS

Mark E. Majerus

USDA-SCS Plant Materials Center, Route 1, Box 1189, Bridger, MT 59014

Sprigging is a vegetative planting method whereby rhizomes, roots, and/or stolons are planted, sprouting new plants from leaf meristem and rhizome nodes. Sprigging is used predominantly in the southern and south-eastern states to establish pastures of bermudagrass *Cynodon dactylon* (L.) Pers. Bermudagrass and bentgrasses (*Agrostis* spp.) are commonly sprigged on golf-course fairways and in other landscaping situations. With sprigging there are numerous factors to consider if plant establishment is to be successful. Some of these factors contributing to poor stand establishment from sprigs are: (i) planting excess dead material (hay and stubble) with sprigs, (ii) drying out of sprigs before and after planting, (iii) overheating of sprigs, and (iv) weed competition with sprouting sprigs (Beaty 1966).

The USDA-SCS Plant Materials Center (PMC) at Bridger, Montana, is testing various techniques of establishing forage plants in wet saline-alkaline soils. With inconsistent establishment from seed, sprigging as an establishment technique was considered. Theoretically, sprigs have a better chance of establishing in salty soils than do seeds because they are planted deeper, below the high concentration of surface salts, and are physically and physiologically more mature than a seedling.

The Bridger PMC purchased a Bermuda King™[1] single-row planter and a Bowie™ 70-cm-wide sprig harvester. All initial testing was done at the PMC in an existing saline seep caused by seepage from an adjacent irrigation canal and perpetuated by poor drainage. Advanced evaluations were conducted on a variety of saline seep discharge areas in Montana and Wyoming. The studies conducted by the Bridger PMC have been separated into the following categories: species trials, sprigging rate and depth, salt-tolerance limits, sprigging at field sites, and sprigging vs. seeding.

Species Trials

The saline seep at the Bridger PMC encompassed approximately .5 hectares. The site is characterized by Electrical Conductivities ranging from 8 to 32 dS/m, the Sodium Adsorption Ratios (S.A.R.'s) ranging from 4 to 6, and a permanent water table fluctuating from 0 to 1 meter.

Methods and Procedures

Initial sprigging trials were limited to those rhizomatous species being grown for foundation seed production at the Bridger PMC, i.e., 'Shoshone' beardless wildrye *Leymus triticoides* (Buckley) Pilger, 'Garrison' creeping foxtail *Alopecurus arundinaceus* Poir., 'Rosana' western wheatgrass *Elytrigia smithii* (Rydb.) Nevski, 'Critana' thickspike wheatgrass *Elymus lanceolatus* (Scribn. & Sm.) Gould, and 'Lutana' cicer milkvetch *Astragalus cicer* L. As native collections were made from halophyte communities throughout Montana and Wyoming, sprigging was done with accessions of alkali cordgrass *Spartina gracilis* Trin. and inland saltgrass *Distichlis spicata* (L.) Greene. Sprigging trials on tailings from a chrome mine included 'Goshen' prairie sandreed *Calamovilfa longifolia* (Hook.) Scribn., PI-478832 mammoth wildrye *Leymus racemosa* (Lam.) Tzvelev, marsh muhly *Muhlenbergia racemosa* (Michx.) B.S.P., and a quackgrass X crested wheatgrass hybrid *Elytrigia repens* (L.) Nevski X *Agropyron cristatum* (L.) Gaertner.

---

[1] Trade names are mentioned solely for the purpose of providing specific information to the reader and do not imply recommendation or endorsement by the U.S. Department of Agriculture.

Results and Discussion

The sprigs of the species tested vary considerably in size, internode length, and fibrous roots. The number of sprigs that can be harvested from a unit area also varies with species. Garrison creeping foxtail is probably the species best adapted to propagation by sprigs. There are numerous nodes along the rhizomes and an extensive fibrous root system at the base of each individual plant. This species will tolerate poorer sprigging conditions than most other species. Inland saltgrass and alkali cordgrass have heavy armored rhizomes that will withstand rough handling and poor soil conditions. Shoshone beardless wildrye is one of the most salt-tolerant species, but does not have the best rhizomes for sprigging. A mature stand has long, coarse rhizomes with a papery covering and very few fibrous roots. Sprigs from 2- to 3-year-old stands are shorter, have more numerous nodes and more fibrous roots, resulting in the best stand establishment. The extensive, fine rhizomes of the quackgrass X crested wheatgrass hybrid are the easiest to dig, and readily establish from sprigs. Establishment has been very poor with sprigs of thickspike wheatgrass, cicer milkvetch, prairie sandreed, and mammoth wildrye.

Sprigging Rate and Depth

Bermudagrass is usually sprigged in rows with at least a 1-meter spacing, and placed 7 to 10 cm apart within the row (Beard 1982). Johnson (1973) found the optimum stands resulted from a 1:50 digging/planting ratio, i.e., stolons and rhizomes from 200 m^2 were capable of planting 1 hectare. Beard (1973) suggested an even lower rate, stating that 1 ft^2 of bermudagrass sod would produce enough sprigs to plant 75 to 80 linear feet of row (1:240 ratio).

Chiles et al. (1966) evaluated planting depth of 0 to 10 cm, concluding that there was a delay in emerging sprouts and a decrease in percentage of sprigs sprouting as planting depth increased from 2.5 to 10 cm. Beard (1982) suggested planting depths of 4 to 5 cm.

Methods and Procedures

The drive mechanism of the sprig planter that feeds the sprigs is driven by a rachet mechanism. To get a uniform, continuous flow of sprigs (10-15 sprigs/meter), the mechanism had to be set at the maximum setting. At lower settings, sprigs were not planted uniformly.

Results and Discussion

All species have been sprigged with the machine set at the maximum setting. On the average, this is a rate of approximately 750 kg/ha.

This varies somewhat with species, moisture content, and the amount of soil in the harvested product. The number of sprigs/volume varies with species. Because of the extensive fibrous roots attached to the rhizomes of creeping foxtail, there are far fewer rhizomes per unit area than there would be of the naked rhizomes of beardless wildrye or western wheatgrass. When digging sprigs, only half of the area was harvested, leaving alternate strips to reestablish the stand. The digging-to-planting ratio ranged from 1:15 for creeping foxtail to 1:25 for the quackgrass X crested wheatgrass hybrid (average 1:18), i.e., sprigs dug from 1 hectare were sufficient to plant 18 hectares using a 1- to 1.25-meter row spacing.

Depending upon the soil firmness or amount of sod or trash on the surface, planting depths have varied from 3 to 10 cm. Although a 10-cm furrow may be dug, there may only be 2 to 5 cm of soil covering the sprigs.

Some alterations were made on the sprig planter to facilitate planting in heavy clay soils and sites with heavy sod or trash. A sharp lip along the edge of the furrow opener was added, as well as the installation of a coulter disk in front of the opener shovel.

Time of Sprigging

In the subtropical climate of the southern states, bermudagrass is sprigged at all times of the year. However, Woodle (1954) and Beaty (1966) found that late winter or early spring sprigging of dormant sprigs produced the best results with warm-season grasses. Beard (1973) stated that cool-season grasses should be sprigged in late summer and warm-season in late spring--these times ensuring the longest period of favorable temperature and moisture conditions for growth and development.

Methods and Materials

The initial sprigging trials were on a saline seep discharge area that was usually saturated or even had standing water in the spring and early summer. Frequently it was late June or July before this site dried out enough to be traversed with a tractor (with dual rear tires) and the sprig planter. Sprigging trials were therefore established in late summer and fall. Replicated rows (three each) of beardless wildrye, creeping foxtail, western wheatgrass, thickspike wheatgrass, and cicer milkvetch were planted across a salinity gradient (E.C.=6-16 dS/m) during the months of July, August, September, and October of 1975. Density counts of sprouting sprigs were made every 3 weeks.

Results and Discussion

Sprigs of thickspike wheatgrass and cicer milkvetch failed to produce new plants regardless of when they were planted. Mid-September was found to be the optimum planting time for this site (table 1). By September, temperatures had dropped considerably and precipitation was more frequent. Enough plants sprouted and established themselves before freezeup. Although a plant density of five plants/meter of row is not very thick, these stands filled in within the row and between rows after two growing seasons. Sprigs planted in October produced new growth, but they may not have been mature enough to survive the winter.

The hot, dry conditions of summer (July and August) were not conducive to propagation by sprigging. Those sprigs that sprouted succumbed to heat and moisture stress.

Table 1. Density of plants sprouting from sprigs planted at four dates in saline soil at the Bridger PMC.

	Stand Densities (Average Plants/Meter of Row							
Sprigging Dates:	July 2		August 8		September 10		October	
Evaluation Dates:	10/31	6/18	10/31	6/18	10/31	6/18	10/31	6/18
Garrison creeping foxtail	.1	.0	1.6	3.0	5.3	5.3	.8	3.5
Shoshone beardless wildrye	.05	.0	.7	1.2	2.7	5.3	1.8	3.2
Rosana western wheatgrass	.0	.0	.3	.5	4.8	4.5	.1	2.2
First Emergence: 1/	55		30		16		14	

1/ Days after planting.

Salt Tolerance Limits

The preliminary sprigging trial (Time of Planting) did not determine the upper salt-tolerance limits of the species used, as they all established some plants along the entire E.C.=6-16 dS/m range. Subsequent trials were established along a more severe gradient.

Methods and Procedures

Sprigs of Shoshone beardless wildrye, Rosana western wheatgrass, and Garrison creeping foxtail were planted (three reps) across a salinity gradient (E.C. range of 9.5-32 dS/m) on 8 September 1976. Row spacing was 1.5 meters apart. The site was a clean, firmly packed fallow area. The following August, foliage was clipped (2-cm stubble) in 3-meter segments along each row, and electrical conductivity measurements were taken at 1-meter intervals with a four-electrode probe. In subsequent years, as the plants filled in between the rows, forage was clipped from 1 m^2 frames at 3-meter intervals along the salinity gradient. After 3 years, the site was completely sodded in and beginning to look chlorotic. In the fall of 1979 and 1981, 55 kg/ha of nitrogen was broadcast.

Results and Discussion

A regression analysis was run correlating increasing soil salinity with decreasing forage production (figure 1). The first year data indicated that the average soil salinity at which emergence ceased was approximately 13 dS/m for Garrison creeping foxtail, 17 dS/m for Rosana western wheatgrass, and 22 dS/m for Shoshone beardless wildrye. Beardless wildrye had some isolated emergence and survival at 30 dS/m.

Within 2 years, all of the rows had grown together forming a mixed grass stand. Beardless wildrye, however, was the only species to spread into the saltiest portion of the site (32 dS/m). Table 2 shows how beardless wildrye dominated the site, increasing in composition each year. This table also shows the significant increase in productivity when 55 kg/ha nitrogen was applied.

A solid, productive stand of beardless wildrye still dominates this site 13 years later.

Figure 1. Regression analysis showing correlation between forage production and electrical conductivity of the surface 30 cm of soil in 1977 sprigging trials.

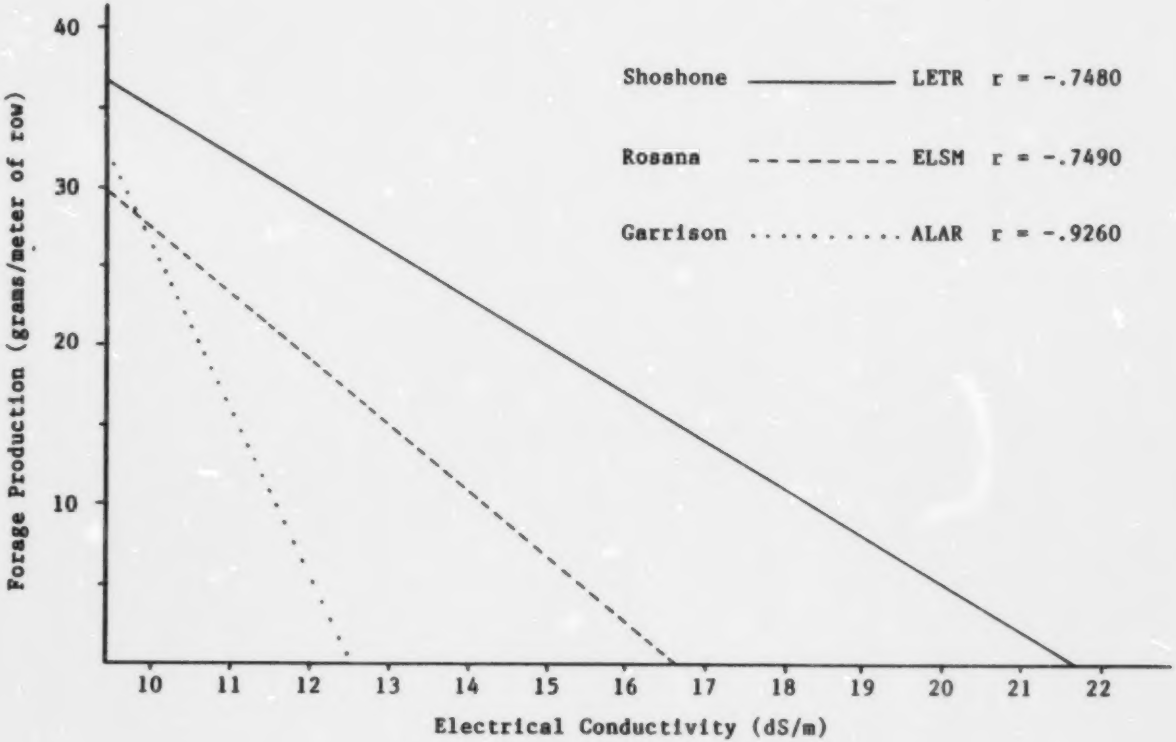


Table 2. Cover estimates and forage production of three sprigged grasses on saline soil at the Bridger PMC.

	Cover Estimates				Forage Production (kg/ha)							
	% Composition				1978		1979		1980		1981	
					E.C.		E.C.		E.C.		E.C.	
	1978	1979	1980	1981	10	25	10	25	10	25	10	25
Shoshone	71	78	81	86)	2221	785	2054	920	6560	5140	5710	4830
Rosana	20	18	11	8)								
Garrison	9	4	8	6)								

Sprigging at Field Sites

To evaluate sprigging on a larger scale and at a variety of site conditions, test sites were established at different saline seeps in Montana and Wyoming.

Methods and Materials

Sprigs were dug from seed production fields at the Bridger PMC and transported to each of the field test sites. Sprigs were dug, put into barrels, tanks, or pickup boxes, wet down, and covered with a tarpaulin. Sprigs were usually planted within 48 hours of digging. Chiles et al. (1966) found that bermudagrass sprigs could be stored dry for up to 2 days, but, if wet, were still viable after 16 days of storage. Chamblee and Gooden (1981) found that exposure to sunlight and high temperatures (34°C) could desiccate bermudagrass sprigs in as few as 6 hours.

Results and Discussion

Among sites there was variation in the salinity levels, soil moisture conditions, and the amount of native or weedy plant competition. Sprigs of Shoshone beardless wildrye, Rosana western wheatgrass, and Garrison creeping foxtail were dug at the Bridger PMC and used at each of the following test sites:

1. Hardin (6 km west of Hardin, Montana)--9/15/76
   E.C. range 45-73 dS/m
   Results: Complete failure--too high salinity
2. Powell (7 km west of Powell, Wyoming)--9/17/76
   E.C. range 12-20 dS/m
   Results: The site was moldboard plowed to turn under barley stubble, creating a rough, dry surface. A sparse stand of beardless wildrye was the only species to establish.
3. Highwood Bench (39 km south of Fort Benton, Montana)--9/22/77
   E.C. range 8-35 dS/m (saturated)
   Results: Garrison creeping foxtail developed an excellent stand on the upper end of the gradient (8-16 dS/m) because of subsurface moisture and the associated salt dilution. Shoshone had its best growth at midslope and was the only species to have emergence in the saltiest portion of the seep.
4. Conrad (3 km west of Conrad, Montana)--9/23/77
   E.C. range 5-25 dS/m (thick sod of foxtail barley)
   Results: Garrison and Shoshone developed only fair stands because of the competition from the foxtail barley.

5. *Malta* (Bowdoin National Wildlife Refuge, Malta, Montana)--9/26/78
E.C. range 3-40 dS/m
Results: Failure because of competition from dense native sod of Nuttall alkaligrass and inland saltgrass.

6. *Power* (5 km north of Power, Montana)--9/23/80
E.C. range 10-45 dS/m
Results: Failure; too dry at time of sprigging.

The results of these field trials have emphasized the necessity of having adequate soil moisture at the time of sprigging, and have shown how competition from native plants or weeds can inhibit plant establishment. Good site preparation that includes chemical fallow or mechanical cultivation is as necessary for sprigging as for seeding.

Sprigging vs. Seeding

Methods and Materials

To determine if better stands can truly be realized with sprigging rather than seeding, comparative studies were established at the Bridger PMC and two field locations. Three rhizomatous grasses (see table 3) were sprigged across a gradient (low moisture-low salinity through high moisture-high salinity) at the Highwood Bench site (eight, 50-meter rows), and Conrad site (eight, 25-meter rows) on 22 October 1977. Drill-width seedings of 12 forage grasses (see table 3) were established at Highwood Bench (10/18/77) and Conrad (10/19/77) using a double-disk drill with depth bands.

On a saline, subirrigated site at the Bridger PMC, a study was established to compare three seeded forage grasses with three sprigged grasses. On 24 September 1982, 40-meter-long rows (three reps) of Shoshone beardless wildrye, 9005564 alkali cordgrass, and a quackgrass X crested wheatgrass hybrid were sprigged along a salinity gradient (E.C. range 5-28 dS/m). On 12 October 1982, the following species were seeded between the sprigged rows: 'Jose' tall wheatgrass *Thinopyrum ponticum* (Podp.) Barkworth and Dewey, 'Kenmont' tall fescue *Festuca arundinacea* Screb., and Shoshone beardless wildrye. Electrical conductivity was measured at 3-meter intervals, and corresponding .6- by 2-meter plots were harvested for forage (15 June 1984).

Results and Discussion

There was considerable difference between the two field sites. The Highwood Bench site was fallow and still actively seeping, while the Conrad site was drying up and dominated by foxtail barley *Hordeum jubatum* L. Certain species did well on the drier site, while others performed best on the wet site (table 3). On the dry site (Conrad), seeded material was just as good as the sprigged, if not better. At Conrad, the seeded Russian wildrye *Psathyrostachys juncea* (Fisch.) Nevski had the best stand. Stands of tall wheatgrass, beardless wildrye (sprigged and seeded), and creeping foxtail (sprigged and seeded) were the only others that had good stands at this site. On the wet site (Highwood), beardless wildrye and creeping foxtail performed the best, with beardless wildrye tolerating the higher salinity better than any other species. Sprigging produced better stands initially, but with the vigorous spreading ability of these two species, the seeded stands were gaining on the sprigged stands.

Table 3. Ratings of sprigged (Sp) and seeded (Sd) stands along a salinity gradient at the Conrad and Fort Benton field evaluation sites, 1981.

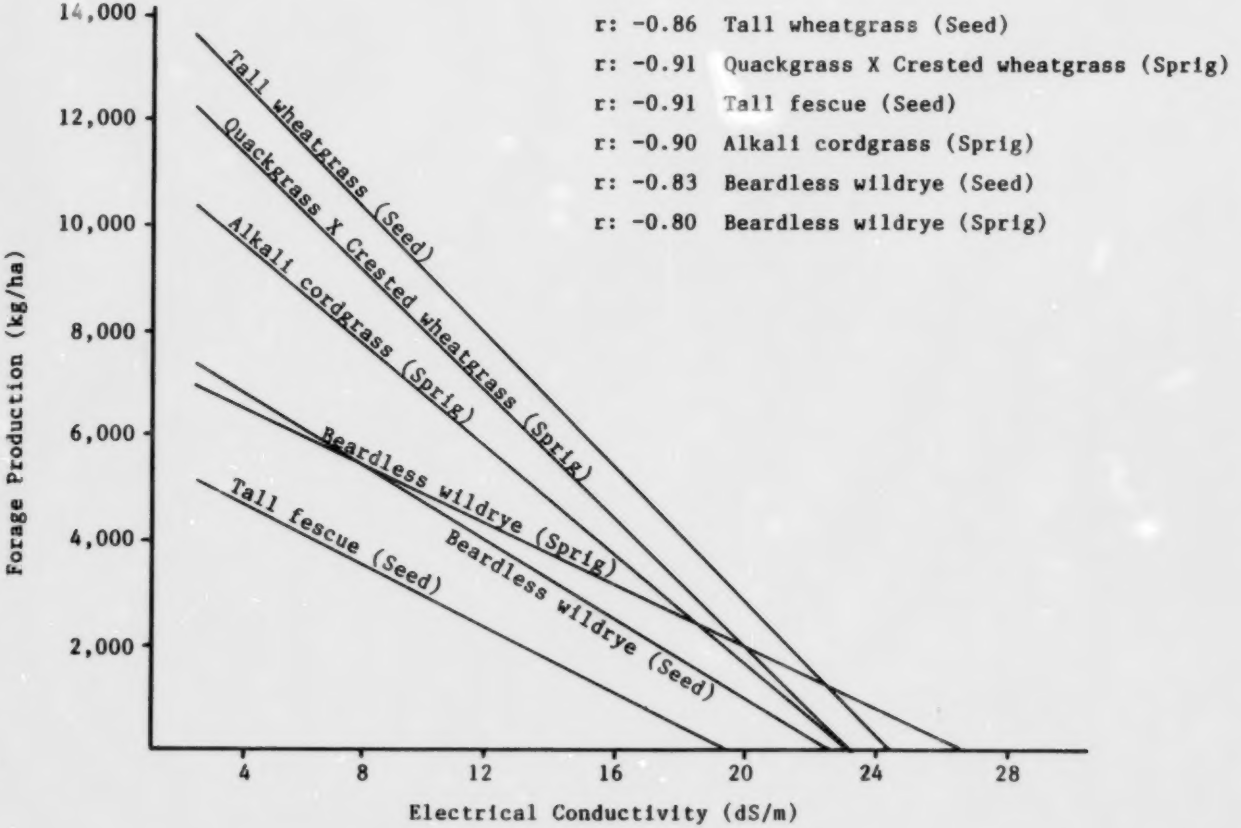
Accession & Common Name	Conrad				Fort Benton					
	Dry E.C.=4-8		Wet E.C.=16+		Wet E.C.=4-8		Wet E.C.=8-16		Wet E.C.=16+	
	Sp	Sd	Sp	Sd	Sp	Sd	Sp	Sd	Sp	Sd
	1/	1/	1/	1/	1/	1/	1/	1/	1/	1/
Parkway Crested wheatgrass		5		4		7		7		8
Alkar Tall wheatgrass		4		2		7		5		8
Rosana Western wheatgrass	8	7	5	3	7	7	8	8	8	8
Revenue Slender wheatgrass		7		7		4		7		8
Garrison Creeping foxtail	3	3	4	4	1	1	2	3	6	7
Prairieland Altai wildrye		4		7		4		6		8
PI-478831 Basin wildrye		5		7		7		8		8
PI-478832 Mammoth wildrye		2		7		6		8		8
Vinall Russian wildrye		1		2		4		7		8
Shoshone Beardless wildrye	7	5	2	2	2	1	1	3	5	5
Kenmont Tall fescue		7		6		2		5		8
PI-434444 Alkali sacaton		9		9		7		7		8

1/ Ratings 1-9 with 1 best.

At the Bridger PMC site, there were significant differences in forage production among species at the lower salinity levels. This difference is an expression of the genetic difference between individual species. As salinity increases, forage is inversely affected (figure 2). Tall fescue was significantly poorer than all other species all along the gradient. The beardless wildrye that was sprigged established at higher salinity levels and was more productive than the stand originating from seed. The second-year data (shown in figure 2) no longer shows the drastic difference in stand establishment between sprigged and seeded that was exhibited the first year. The few plants that sprouted from seed in the higher salinity levels have since spread, in 2 years producing a stand that was similar to that produced by the sprigged stand in only 1 year.

Today, 7 years after sprigging/planting, this site is dominated by Shoshone beardless wildrye, with some tall wheatgrass in areas with E.C. less than 20 dS/m.

Figure 2. Sprigging vs. Seeding at Bridger PMC. Correlation of air-dried forage samples with the corresponding electrical conductivity measurements.



Summary

Sprigging has been found to be a feasible method for establishing rhizomatous forage grasses in saline seep discharge areas and other wet, saline-affected areas. However, the site conditions are even more critical for sprigging than seeding. Because most seep areas are saturated in the spring and early summer, fall planting (mid-September) has produced the best results. Soil moisture at the time of sprigging is the most critical factor, requiring a near-field-capacity level to keep from desiccating the sprigs. Competition from weeds, native plants, or even dead sod hinders plant establishment. The seedbed prepared for sprigging should be no different than that which would be prepared for seeding, i.e., fallow, weed-free, packed, and with good soil moisture. Although the Bridger PMC has not done any large-scale plantings to determine the economic feasibility of the sprigging technique, it is apparent that a source of sprigs needs to be relatively close to any sprigging site.

Shoshone beardless wildrye has been the most successfully sprigged species in very saline soils (16+ dS/m). Garrison creeping foxtail is best suited for newly developing seeps where soil salinity has yet to build up to 12-14 dS/m.

Sprigging as a planting technique is presently being tested on chrome tailings (inert sand), fluctuating shorelines of large reservoirs, reestablishment of breeder blocks for seed production, and interplanting in deteriorated high mountain meadows.

Literature Cited

1. Beard, James B. 1973. Turfgrass: science and culture. Prentice-Hall, Inc. Englewood Cliffs, NJ.
2. Beard, James B. 1982. Turf management for golf courses. Burgess Publishing Co., Minneapolis, MN
3. Beaty, E. R. 1966. Sprouting of coastal bermudagrass stolons. Agron. J. 58:55-556.
4. Chiles, R. E., W. W. Huffine, and J. A. Lynd. 1966. Differential response of *Cynodon* varieties to type of sprig storage and planting depth. Agron. J. 58:231-234.
5. Chamblee, D. S., and D. T. Gooden, III. 1981. Desiccation, temperature, and degree of dormancy of sprigs influence on establishment of coastal bermudagrass. Agron. J. 73:872-876.
6. Johnson, B. J. 1973. Herbicides, sprigging rates, and nitrogen treatment for establishment of tifway bermudagrass. Agron. J. 65:969-972.
7. Woodle, H. A. 1954. Coastal bermudagrass. Clemson Agric. Col. Bull. 374.

ASSESSMENT OF SALINITY IN THE PASQUIA SOIL AND WATER MANAGEMENT PROJECT

Bill Harron, Soil Salinity Specialist, PFRA Regina
Erwin Allerdings, Area Soil Conservationist, PFRA Dauphin

The Agri-Food Subsidiary Agreement as part of the Economic Regional Development Agreement provided funding for soil conservation activities throughout Manitoba for the past 5 years. The Pasquia Soil and Water Management Project was initiated in 1987 under Agri-Food. The Pasquia project has a number of objectives relating to the overall soil conservation effort in Manitoba, but the main emphasis of this paper is on assessment of soil salinity in the Pasquia Land Settlement, particularly in Polder III.

The salinity assessment of Polder III in the Pasquia settlement had two major objectives. The first was to prepare a regional salinity assessment for Manitoba Crown Lands for input into their policy for disposition of newly drained, agricultural land in Polder III. The other objective was to provide recommendations for salinity control on presently cropped land within the Pasquia Soil and Water Management Project.

Background

The Pasquia Land Settlement is located in west-central Manitoba along the northwestern edge of the Manitoba lowland region that was covered by the glacial lake Agassiz. The Saskatchewan River basin, which drains most of southern Alberta and part of central Saskatchewan, culminates with the formation of a large delta. The Saskatchewan River delta is split by a large glacial moraine on which The Pas townsite is presently located. The Pasquia Land Settlement was developed on the west side of this moraine. Frequent floods combined with a very inadequate drainage system made farming during the early settlement years a real gamble.

The Manitoba government and PFRA embarked on the Pasquia Reclamation Project in 1956 after a series of particularly wet years during the late 1940's and early 50's. This reclamation effort has resulted in a highly efficient drainage system for the 54,000 acres in Polder I and II. The third phase of reclamation in the Pasquia Land Settlement, called Polder III east, was initiated in 1988. The 23,500 acres in Polder III east will be drained with the assistance of another 200 c.f.s. pumping station and further expansion of the existing drainage network.

Polder III east is dominated by Pasquia Lake (Figure 1). Drainage of this lake will control spring flood waters allowing a large block of land to be available for annual crop production. Currently the land is primarily used for grazing or native hay production. The efficiency of this proposed drainage system has a direct bearing on the soil salinization process by its control of the water table.

Historical Perspective

There is always merit when dealing with land resource problems, to contact old-time residents of the area and get their perceptions. Here are some of those recollections:

> *"(Fire in 1936) burned out everything. Peat kept burning for 4 or 5 years. Salty clay started to show up everywhere after that."*
>
> *Steve Nikolychuk, farming since 1943.*

> *"Five to six bare patches were black like coal. Wouldn't even grow pigweed."*
>
> *Elroy Uffelman, farming since 1950.*

Both Mr. Nikolychuk and Mr. Uffelman remember significant patches of "sour" land in the late 40's throughout the Pasquia Land Settlement, but particularly in the south western portion. The exposure of most of this saline lacustrine material seems to have occurred after an intense surface fire combined with 4 or 5 years of peat ground fires. Mr. Nikolychuk notes that early reclamation attempts of the saline soils included moving unburned peat mounds and hauling manure to these sites. Photo-records (1956-58) from PFRA Information Services, Regina, confirm the existence of sparsely vegetated sites throughout Polder III.

A number of past studies relating to saline soils of the Pasquia area have been completed. Ehrlich, et.al. (1960) identified a total of 10,595 acres of moderately and strongly saline soil in The Pas and Pasquia soil series in their soil survey of the Pasquia map area. The Canada Department of Agriculture also initiated a study of crop rotation options on saline soils (Spratt, et.al 1970). Their main conclusion was that saline soil can be made more productive if a legume is included in the cropping sequence. Another study of salinity in the Pasquia Lake area by Mills, et.al. (1984) further refined our understanding of the saline conditions found in Polder III.

Regional Assessment

The approach of the regional salinity assessment was to develop a relationship between the landform, hydrogeology, soils, vegetation and land use. Soils, vegetation and land use reflect the interaction of the landform and hydrogeology, and can be used to extrapolate the interpretations across the landscape.

The regional assessment consisted of two major components, hydrogeologic investigations to determine the cause of salinity in the Pasquia Project and a saline-land mapping to delineate the areas suitable for agricultural development based on soil salinity factors. A hydrogeologic investigation was conducted and the mapping was confirmed with aerial survey and ground inspections. Ground water studies in the Pasquia area had noted the presence of saline water. In his report in 1973, A. Pederson noted that:

> *"a saline water flow system enters the area from the southwest"*
>
> *and*
>
> *"upward movement of saline water appears to occur where there is little or no lacustrine clay."*

Although there had been several wells drilled for domestic supply and data from previous studies, little data existed within Polder III.

To augment existing data a drilling program was conducted by the Geology and Air Surveys Division of PFRA. (Stilwell, 1987). Two piezometers were installed in SW 14-54-28 W1 in a saline "hot-spot", to a depth of 55 m (RD10) and 22 m (RD11) respectively. Shallow water table wells (6 m) were also installed using existing water well data, an west-east cross section was developed (Figure 2).

The Pasquia area is underlain by the Interlake formation, a silurian dolomite. The surface of this formation is highly fractured and pockets of rubble are present. The dolomite is overlain by a discontinuous glacial till similar to the till ridge south of The Pas along Highway #10. Overlying the till is a thick lacustrine clay that was deposited as part of the Agassiz basin. The sequence is topped by interbedded sands, silts and clays of the Saskatchewan River Delta.

Piezometric head at RD10 is 3 meters above groundsurface, while RD11 reads 0.5 m above ground. Shallow wells indicate that the natural ground water is at 1.0 m below ground surface, providing a strong upward gradient for flow.

Artesian pressure can cause salinity by several mechanisms. The upward gradient prevents downward flow resulting in an evaporative pan, leaving the local salts in place. The effect of local systems can be enhanced by the presence of artesian pressure. Otherwise, upward flow will bring salts into the saline areas resulting in concentration of salts as discharge waters evaporate. Objective of this component was to determine the dominant mechanism of salinization.

Water quality analysis showed that the water in the dolomite (RD10) is dominantly sodium chloride (NaCl) (Figure 3) and the till (RD11) is a magnesium-sodium sulphate system (Stilwell, 1987). A shallow surface well outside the saline area had very low salt content and had calcium carbonate ($Ca(HCO_3)_2$) dominated water, therefore within Polder III, three chemical systems are present.

Three shallow (6.0 m) wells had been installed at the Vic Jory detailed investigation site (N½ 2-54-28 W1). They were located to form a transect from severely saline (VJ6), moderately saline (VJ4) and slightly saline (VJ1). The water analysis (Figure 3) showed a transition from a dominantly chloride system at VJ6 to a bicarbonate system at VJ1. The chemistry at VJ6 is similar to the water quality of the dolomite at 50 m below ground surface. Therefore the water from the dolomite is reaching the surface bringing the chloride salts and depositing them in the saline "hot-spots". Salt tolerant plants, especially red samphire and foxtail barley, growing in the areas show the high chloride content by the reddish tinge on the foliage. Therefore, the cause of salinity in Polder III has been confirmed as direct discharge of saline waters from underlying bedrock aquifers. At certain areas the flow is sufficient to form saline "hot-spots". Historic observation shows that many of these saline areas were covered by peat and only appeared after the peat was burned.

Saline Landscape Mapping

The major tool for identifying saline areas in this project was the electromagnetic terrain conductivity meter (EM38) developed by Geonics Ltd. EM meters measure salinity by inducing an electric current in the soil. The strength of the current received by the meter is a measurement of the conductivity of the soil. Soil temperature, texture, moisture content and mineralogy can affect the reading, but most of the response is due to soil salinity. The EM 38 detects soil salinity to a depth of 1.2 to 15.0 m in the vertical position.

A correlation of soil samples (0-100 m) and EM 38 reading was done to determine the accuracy of the reading and to relate meter readings with standard salinity values. Figure 4 shows the relationship between EM and EC. Ninety percent ($r^2 = 0.90$) of the EM readings can be attributed to the soil salinity. The following EM values were used for mapping the severity of salinity in Polder III.

EM Reading	Corresponding EC Value	Interpretation
<100	<2 d s/m	non-saline
100-150	2-4 d s/m	slightly saline
150-200	4-8 d s/m	moderately saline
>200	>8 d s/m	severly saline

For mapping purpose, the slightly and moderately saline areas were grouped. The variability in these areas made it difficult to delineate between them. Three obvious landscape units separated out from this classification.

The non-saline areas were primarily the elevated level which are mixed boreal forest. These areas were well drained because of coarser soil texture (silts and sands) of the alluvial material and the higher topographic position. These areas could be released for agricultural development.

The slightly and moderately saline areas occur on the fine textured alluvial deposits (clays, silty clays). Drainage is imperfect to poorly drained. Willows are common with slightly saline soils (EM readings 100-150) but as salinity increases, grasses predominate. These areas are suitable for improved forages and grazing. Considerable native hay production has been obtained from these lands in the past. After improved drainage works are complete, the slightly saline areas could be suitable for annual cropping as shown by the detailed site investigations.

The severely saline areas are obvious by the sparse vegetation of salt tolerant grasses and the presence of salicornia (red samphire). These areas will continue to be low productivity areas and are not recommended for release of annual cropping. Grazing pressure on this land could decrease productivity through soil disturbance by cattle traffic. Improvements in forage production may be possible by directly seeding salt and flooding tolerant grasses (Garrison creeping foxtail or Read canary grass).

Detailed Assessment of Existing Salinity

Eleven applications covering 1350 acres were received by the Pasquia Soil and Water Management Project. These sites had exhibited a range of salinity problems as identified by the producers. For this report, three typical sites were chosen to demonstrate the range of on-farm salinity problems in Polder III.

The salinity investigation consisted of an EM survey

(EM 31 and EM 38), soil sampling and analysis and the installation of shallow water table wells for monitoring. The EM readings were contoured and mapped for each site, using the ranges of severity developed for the regional assessment.

Slightly Saline Site

A typical slightly saline soil condition can be found on Alvin Helstrom's hay land located on Lots 37 and 38-54-28-W1. Prior to 1980, Mr. Helstrom grew annual crops on this acreage with increasingly greater and greater acreage being affected by soil salinity. In 1980, he seeded the entire area to an alfalfa-bromegrass mixture. The results, as shown by the EM 38 readings in Figure 5, indicate that this land management practice has significantly reduced the surface expression of salinity on this site. He is presently considering his options for pasture rennovation with a short period of annual cropping for weed control. It was recommended that he minimize his fallow period after breaking and consider re-establishment of forages.

It is interesting to note higher levels of surface soil salinity on the east end of the parcel. This triangle of cropland has been continuously cropped for a number of years but yet salinity levels are higher than the adjacent haylands. This parcel of annual cropland is the original site of the Canada Department of Agriculture study during the 1960's (Spratt, et.al., 1970). This practical comparison of the effect of land management practices validates the conclusion that these researchers had three decades ago.

Moderately Saline Site

Larry Paterson's farmland on the N.W. 6-55-28-W1 provides a good example of a moderately saline site. A slightly saline soil condition with patches of moderate salinity has been evident on this field for a number of years. This is expressed by the poor germination and subsequent poor growth of a variety of annual crops in certain portions of the field. The EM 38 vertical mapping aided in pinpointing the problem spots in the field (Figure 6).

Mr. Paterson and his father historically have summerfallowed this land every third year, particularly those sites where germination was poor. These practices have likely exacerbated the situation where soil salinity already has a natural tendency of increasing. It is recommended that Mr. Paterson continuously crop most of his land and establish a forage stand on his moderately saline spots. Green manuring, as part of the crop rotation, will also be beneficial on this parcel both from the standpoint of fertility improvement and the reduction of surface crusting.

Installation of four water table wells and measurements over a 3-year period verified the shallowness of the water table in the spots where moderate salinity was predominate (Figure 5) Minor drops in topographic relief when combined with constant water table fluctuations at or near the soil surface seem to develop higher levels of soil salinity. A scenario is developed that allows for the increase of soil salinity by a constant contribution of soil moisture to the surface from the water table through the mechanism of capillary rise.

Severely Saline Site

One of the best examples of severely saline land is located on Vic Jorie's (deceased) farm on the N½ 02-54-28-W1. Mr. Jory has had to contend with highly saline conditions on the west end of the parcel over the past 20 years (Figure 8). Repeated poor annual crops have forced the producer to summerfallow every second year with little organic matter production during the crop year. Three years ago, after another dismal barley crop, Mr. Jory approached the Pasquia Soil and Water Management Project about re-establishing forages.

It was recommended that a series of three lateral drains be installed to reduce problems with excess surface water. Also, application of livestock manure to the area was suggested to improve potential of site reclamation with saline and moisture tolerant forages.

Recommendations

A summary of our recommendations for salinity control on cropped lands within the Pasquia Soil and Water Management Project is included on Table 1.

Salinity Interpretation	EC Value	Beneficial Practices	Best Land-Use
Non-Saline	< 2d s/m	--	Annual Cropping
Moderately Saline	2-8d s/m	Green Manure Livestock Manure	Permanent Forages for Hayland or grazing (include Alfalfa) or Continuous Cropping with Forage in Rotation
Severely Saline	>8d s/m	Surface drainage Livestock manure Sprigging	If cropped, saline and moisture tolerant forages. Otherwise, maintain as native pasture.

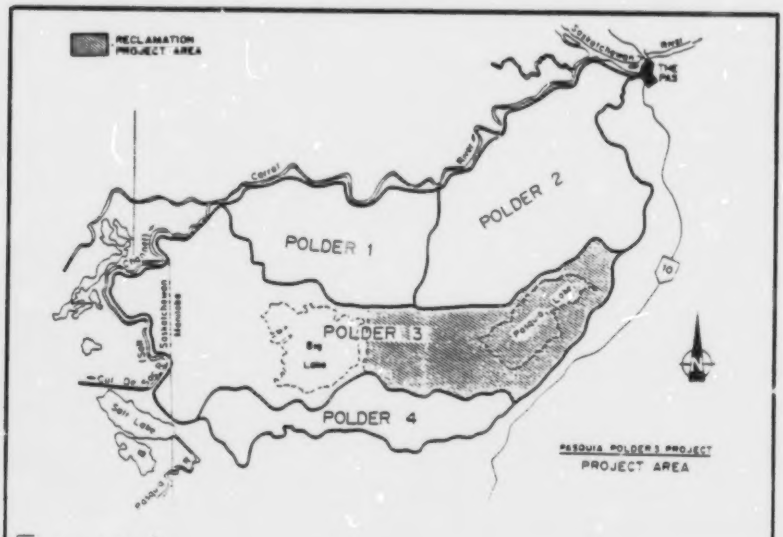

RECLAMATION PROJECT AREA
Saskatchewan
River
THE PAS
Carrot
River
POLDER 1
POLDER 2
POLDER 3
POLDER 4
Big Lake
Pasquia Lake
10
Saskatchewan
Manitoba
Cut De Sac
Salt Lake
Pasquia
N
PASQUIA POLDER 3 PROJECT
PROJECT AREA

Figure 1

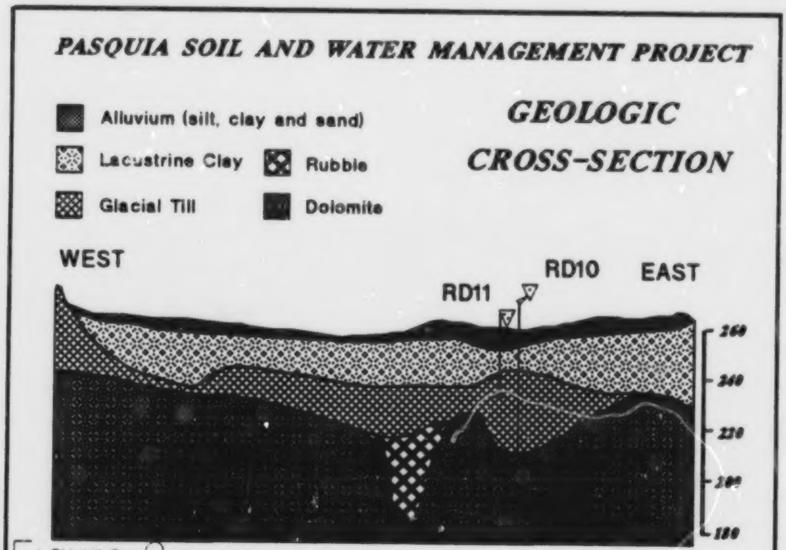

PASQUIA SOIL AND WATER MANAGEMENT PROJECT
GEOLOGIC CROSS-SECTION
Alluvium (silt, clay and sand)
Lacustrine Clay
Rubble
Glacial Till
Dolomite
WEST
EAST
RD11
RD10
260
240
220
200
180

Figure 2

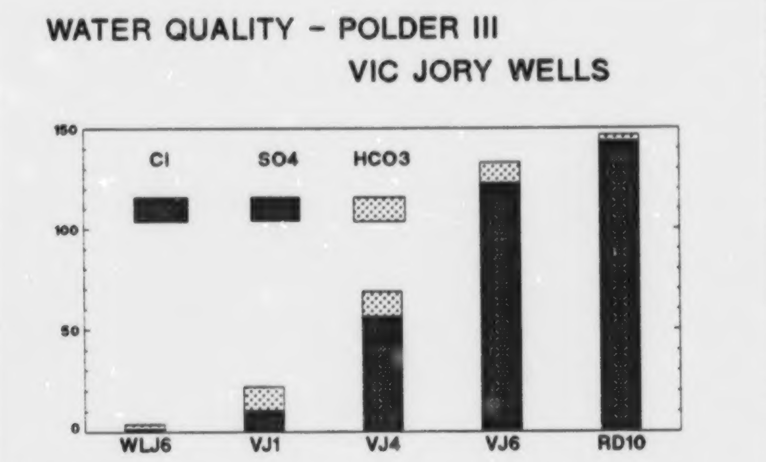


Figure 3

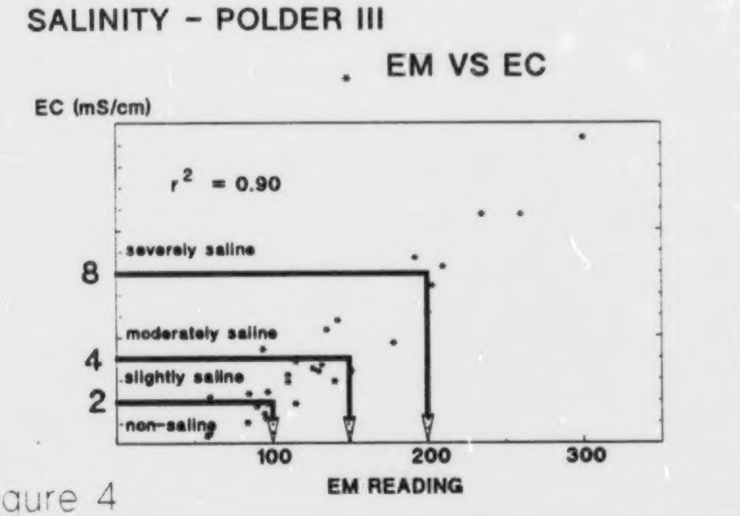


Figure 4

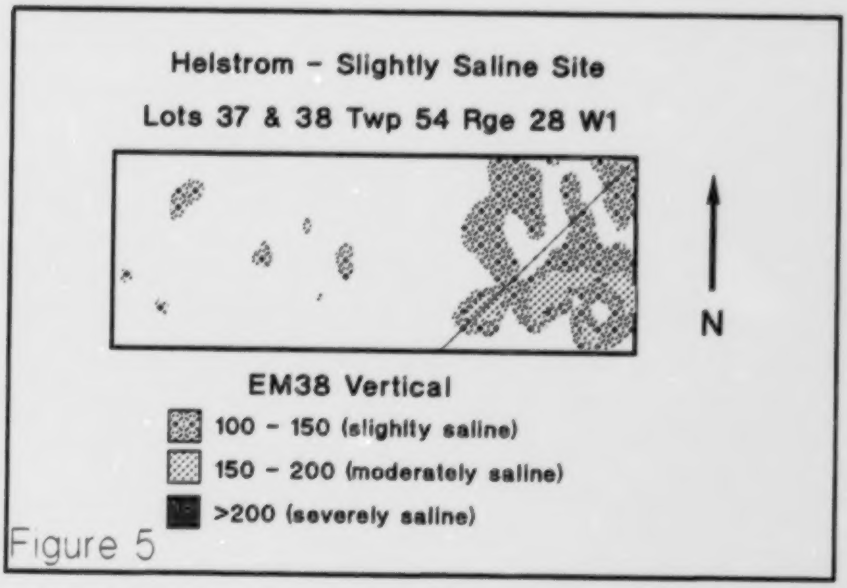

Helstrom - Slightly Saline Site
Lots 37 & 38 Twp 54 Rge 28 W1
N
EM38 Vertical
100 - 150 (slighlty saline)
150 - 200 (moderately saline)
>200 (severely saline)

Figure 5

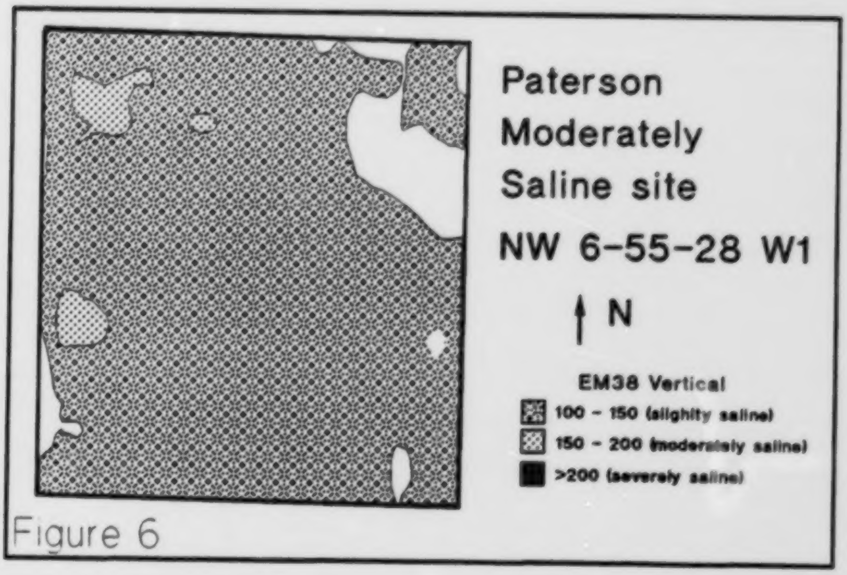

Paterson
Moderately
Saline site
NW 6-55-28 W1
N
EM38 Vertical
100 - 150 (slighlty saline)
150 - 200 (moderately saline)
>200 (severely saline)

Figure 6

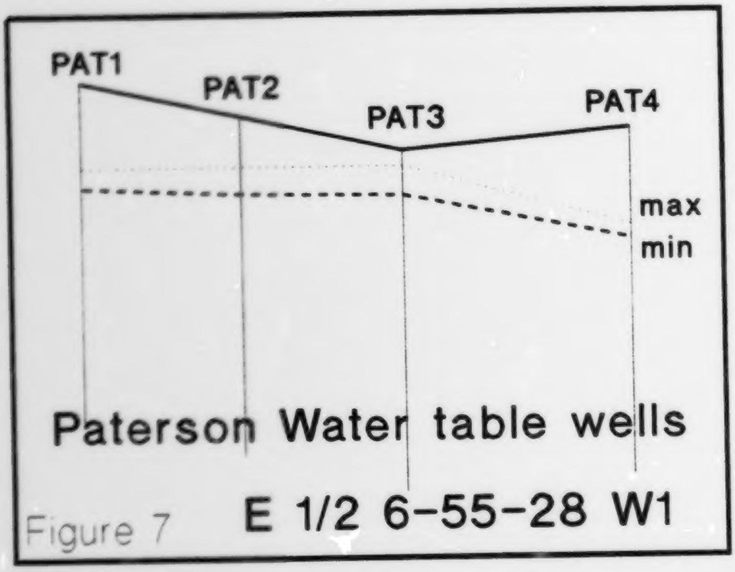

PAT1
PAT2
PAT3
PAT4
max
min
Paterson Water table wells
E 1/2 6-55-28 W1

Figure 7

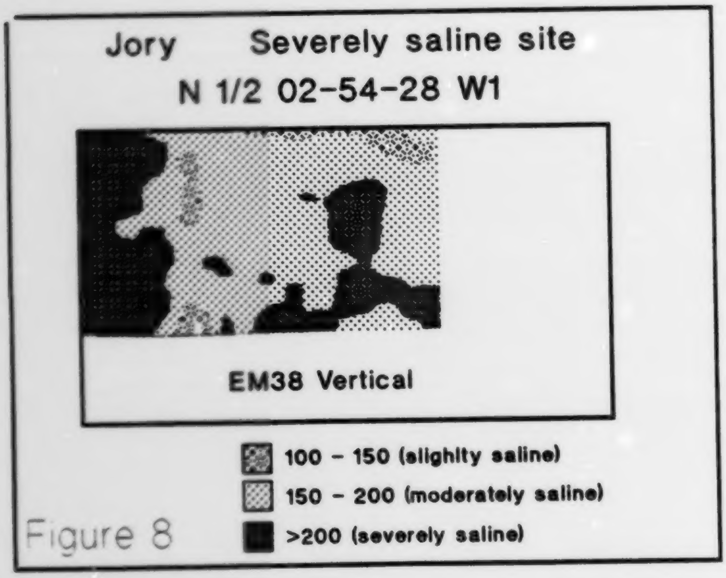

Jory Severely saline site
N 1/2 02-54-28 W1
EM38 Vertical
100 - 150 (slighlty saline)
150 - 200 (moderately saline)
>200 (severely saline)

Figure 8

References -

Ehrlich, W.A., L.E. Pratt, F.P. LeClair and J.A. Barr. 1960. Report of Detailed Soil Survey of Pasquia Map Area in Northern Manitoba. Manitoba Soil Survey Report No. 11.

Mills, G.F., R.G. Eilers and N. Lindberg. 1984. Soil and Salinity Conditions in the Pasquia Lake Area of Polder III, Pasquia Land Settlement Project. Soils Report No. R28.

Pederson, A., 1973. Groundwater Availability in The Pas Area. Groundwater Availability Studies Report No. 9. Water Resources Branch, Dept. of Mines, Resources and Environmental Management. 33pp. and maps.

Spratt, E.D., B.J. Gorby, and W.S. Ferguson. 1970. The Effects of Cropping System on Productivity and Salinity on a Poorly Drained Alluvium Soil. Manitoba Soil Science Meeting, Winnipeg.

Stillwell, W.R. 1987. Departmental Memorandum, PFRA - Agriculture Canada.

SELECTION OF NATIVE AND INTRODUCED PLANTS FOR SALINE-ALKALINE SOILS

Mark E. Majerus

USDA-SCS, Plant Materials Center, Route 1, Box 1189, Bridger, MT 59014

Soil salinity has removed several thousand hectares of prime agricultural land from production in the northern Great Plains states (Montana, North and South Dakota, and Wyoming) and south-central Canadian provinces (Alberta, Saskatchewan, and Manitoba). The formation of saline seeps is strongly correlated to the geology of the affected region and is aggravated by the crop-fallow, dryland farming system. Salinity is also affecting a substantial number of hectares of heavy, poorly drained, irrigated soils along the major river drainages.

Salt-tolerant, perennial, forage crops established on saline-affected soils provide erosion protection, compete with undesirable weeds, utilize excess soil moisture, and, in some instances, can provide a forage crop. Very few forage species have been bred or selected specifically for their salt tolerance, but rather for optimum performance on better quality soils. Researchers, in the past, have concentrated on testing the salt tolerance of various released cultivars. Throughout the northern Great Plains region, the most successful forage grasses have been tall wheatgrass *Thinopyrum ponticum* (Podp.) Barkworth and Dewey, Russian wildrye *Psathyrostachys juncea* (Fisch.) Nevski, and slender wheatgrass *Elymus trachycaulus* (Link.) Gould ex Shinners (Rauser and Crowle 1963) (Forsberg 1953) (Dewey 1960) (Kilcher et al. 1956) (Palmer et al. 1968). McElgunn and Lawrence (1973) compared Altai wildrye *Leymus angustus* (Trin.) Pilger to the other forage grasses commonly used for saline soils. Numerous native and introduced species have been tested for their adaptation to roadsides salinized by winter salt application (Greub et al. 1985) (Hughes et al. 1975). The salt tolerance of the major agricultural crops (field, grain, oil, and forage) have been evaluated by Maas and Hoffman (1977), Borrelli and Brosz (1983), Berstein (1964), and Holmes (1983).

The USDA-SCS Plant Materials Center (PMC) near Bridger, Montana, began to evaluate the salt tolerance of both native and introduced forage plants in 1975. The objective of this project was to develop a more diverse selection of plant materials for use on saline-affected soils throughout the states of Montana and Wyoming.

Assemble and Evaluate

Methods and Materials

The source of plant materials, both seed and vegetative material, was from SCS Plant Materials Centers, the USDA Agricultural Research Service, universities, and collections from native halophyte communities in Montana and Wyoming. Foreign plant materials were received via the National Plant Materials Center at Beltsville, Maryland, and Plant Introduction Stations at Ames, Iowa; Geneva, New York; and Pullman, Washington. During the first 3 years, 460 accessions of 175 species were assembled, including 85 foreign collections and 140 new collections from native halophyte communities in Montana and Wyoming (see appendix A). The majority of the other accessions were released cultivars of forage plants.

A natural saline area (.5 hectares) has developed on the Bridger PMC. This wet-saline site was created by seepage from an adjacent irrigation canal and perpetuated by the poor drainage of the heavy clay soil and history of continuous summer fallowing. There was a perched water table at 40 to 50 cm during the growing season that dropped to about 1 meter in the winter. The electrical conductivity (E.C.) of the surface 15 cm ranged from 10 to 30 dS/m with Sodium Adsorption Ratios (S.A.R.) of 4 to 5. The Bridger area has a growing season of approximately 135 days and an annual precipitation of 29 cm. The soils are a Heldt silty clay loam.

Each accession was seeded with a single-row, belt seeder in individual, 5-meter rows in the wet-saline site and in a control site (irrigated with no salinity). Seedings were made on 11 June 1975, 1 February 1976, 20 October 1976, and 16 November 1977 as seed was collected or received. Each accession was periodically evaluated for time of emergence, seedling vigor, percent stand-density counts, survival, forage production, spread, regrowth, and seed production. Evaluations continued for 5 years to monitor the mortality as plants succumbed to the severe saline conditions. Only the most salt-tolerant accessions were considered for advanced evaluation.

Results and Discussion

There were differences in emergence and survival among different plantings, depending upon the time of planting and the subsequent precipitation patterns. Spring planting was not an alternative because the site was always too wet. Planting in early June, once the site had dried out on the surface, produced the poorest results (13% survival after 2 years). Plantings made in late fall or during snow-free periods in midwinter, followed by a wet spring, had 70 to 75% emergence and survival after 2 years. Fall plantings followed by a dry winter and dry, hot spring resulted in only a 10% survival.

On wet-saline areas, dormant fall plantings (after October 10), followed by a cool, wet spring, produced the best results. Many species [especially beardless wildrye *Leymus triticoides* (Buckley) Pilger] require a wet, cold stratification period to break seed dormancy. Spring moisture is also critical because of its diluting effect on surface salts during the critical germination and emergence period.

The majority of the foreign collections and those from salt marshes of both the Pacific and Atlantic coastal areas winterkilled. Several accessions with known poor salt tolerance were planted as standards of comparison. There were only a few released cultivars that performed well (table 1), which included the most commonly used species for the northern latitudes, i.e., tall wheatgrass, Russian wildrye, and slender wheatgrass. Alkali sacaton, the only warm-season grass, was often difficult to establish because of hot, dry conditions when it germinated and emerged. The accessions that did the best were primarily the native species indigenous to halophyte communities in Montana and Wyoming.

Table 2 lists the nonreleased accessions that exhibited good establishment, survival, and longevity. Two of these accessions have since been released to the commercial market for conservation use on saline-affected sites, i.e., 'Shoshone' beardless wildrye (1980) and 'Pryor' slender wheatgrass (1989).

Although the two legumes are not native to Montana, they were collected from sites where they have naturalized, having been introduced in the early 1900s. Work is being done on how to break seed dormancy on Ruby Valley pointvetch. Scarification, stratification, and fungicide treatments are used to try to improve field germination and emergence.

Table 1. Released cultivars that had superior performance (from seed) on wet-saline soils at the Bridger PMC.

Genus and Species	Common Name	Cultivar
Psathyrostachys juncea (Fisher) Nevski	Russian wildrye	Vinall, Sawki, Mayak
Leymus racemosa (Lam.) Tzvelev	mammoth wildrye	Volga
Thinopyrum ponticum (Podp.) Barkworth and Dewey	tall wheatgrass	Jose, Largo, Alkar, Orbit, Platte
Elymus trachycaulus (Link) Gould ex Shinners	slender wheatgrass	Revenue
Sporobolus airoides (Torr.) Torr.	alkali sacaton	Salado, Saltalk
Atriplex canescens aptera 1/ (Nels.) Hall and Clem.	fourwing saltbush	Wytana
Leymus angustus (Trin.) Pilger	Altai wildrye	Prairieland

1/ Salt-tolerant, but will not tolerate a high water table.

Table 2. Species (nonreleased) that exhibit best emergence (from seed), survival, and longevity on wet-saline soils at the Bridger PMC.

Shoshone	beardless wildrye	Leymus triticoides (Buckley) Pilger
Pryor	slender wheatgrass	Elymus trachycaulus (Link) Gould ex Shinners
	plains bluegrass 1/	Poa arida Vasey
	alkali bluegrass 1/	Poa juncifolia Scribn.
	Nuttall alkaligrass 1/	Puccinellia airoides (Nutt.) Wats. & Coult.
	alkali sacaton 1/	Sporobolus airoides (Torr.) Torr.
	strawberry clover 1/	Trifolium fragiferum L.
	Ruby Valley pointvetch 1/	Oxytropis riparia Litv.
	Swainson pea 2/	Swainsonia salsula (Pallas) Taubert
	Siberian salttree 2/	Halimodendron halodendron (Pallas) Voss
	Gardner saltbush 3/	Atriplex nuttallii Wats.

1/ Seed presently being increased for larger scale field testing.
2/ Removed from testing program because of aggressive and weedy nature.
3/ Salt-tolerant, but will not survive high water table.

Seed Mixture Trials

Salt-tolerance testing of forage grasses and legumes is usually done by testing each species individually under known saline conditions. Very little is documented on the compatibility of individual species when included in a seed mixture. The Bridger PMC and Soil Conservation Districts were making seed mixture recommendations without knowing the compatibility of the individuals in the mix.

Holm (1983) made up mixtures based on seed size: small (alfalfa, sweetclover, and weeping alkaligrass), medium (Russian wildrye, slender wheatgrass, crested wheatgrass, and beardless wildrye), and large (Altai wildrye, tall wheatgrass, and smooth brome). On test sites with electrical conductivity of 10 and 12 dS/m, all species were represented in the resulting stands.

Methods and Materials

As part of a large-scale, saline seep, technology-transfer project (Stillwater Saline Seep Project), plots were established on a saline seep discharge area to evaluate three seedbed preparation techniques and four seed mixtures. The test site is located in Wheat Basin, 12 km east of Rapelje, Montana. There is a soil moisture (dry to wet) and salinity gradient (E.C.=6 to 35 dS/m) across the saline seep discharge area. The seedbed preparations (three reps) consisted of a control (weeds mowed), mechanical fallow (fallowed with sweeps), and chemical fallow (sprayed with 2% Glyphosate). On 23 October 1985, four seed mixtures were seeded with a double-disk drill (2-meter width). Mixture 1 was a mix of the most commonly used species; Mix 2 of species preferring wet-saline soils; Mix 3 of species preferring dry-saline soils, and Mix 4 of a simple mix of two grasses and one legume (table 3).

Table 3. Mixtures seeded on three seedbed preparation treatments across a salinity gradient in a saline seep discharge area near Rapelje, Montana.

Mixtures	kg/ha	Mixtures	kg/ha
Mix 1		Mix 2	
Shoshone beardless wildrye	3.4	Shoshone beardless wildrye	5.6
Jose tall wheatgrass	4.5	Kenmont tall fescue	3.4
Pryor slender wheatgrass	2.1	Garrison creeping foxtail	1.1
Prairieland Altai wildrye	4.5	Pryor slender wheatgrass	4.5
Kenmont tall fescue	1.1		
Mix 3		Mix 4	
Jose tall wheatgrass	4.5	Shoshone beardless wildrye	5.6
Prairieland Altai wildrye	4.5	Prairieland Altai wildrye	6.7
Vinall Russian wildrye	3.4	9005617 strawberry clover	2.2
Pryor slender wheatgrass	3.4		

Each year forage was sampled and species composition was estimated in .6 X .6 m plots at three positions along the gradient for each seed mix and seedbed preparation treatment. Soil samples (0-15 cm) were taken at each sample site and analyzed for electrical conductivity.

Results and Discussion

During the establishment year (1986), it was possible to row all of the seeded material, but because of extensive cropping by grasshoppers, it was difficult to distinguish which seed mixture or site preparation had the best performance. The first 3 years of the study were unseasonably hot and dry. These drought conditions have favored those species that are more drought hardy. The species that require a wet soil profile (beardless wildrye and creeping foxtail) are present, but are not as productive as would be expected on an active seep.

During the first 3 years, there were no significant differences in forage production among the seedbed preparation treatments (figure 1a). However, in 1989 the production on the mechanical and chemically fallowed sites had significantly higher production than that of the control. Competition from weeds, primarily foxtail barley, is taking its toll in the control treatment.

The drought period had a definite effect on which mixtures performed the best (figure 1b). Mixtures 1 and 3, which contained tall wheatgrass, had the best overall production. The increase in production of Mix 3 in 1989 can be attributed, in part, to Russian wildrye. Creeping foxtail and beardless wildrye plants are present in Mixtures 2 and 4, but will not proliferate themselves until soil moisture conditions improve.

The expected inverse effect of soil salinity on total forage production was not apparent, as there was very little difference in production as the gradient changed from 6-10 to 10-16 to 16-20 dS/m (figure 1c). The drought conditions produced moisture stress at the dry/low salinity end of the gradient. Soil moisture conditions improved as the salinity level increased. Available soil moisture was the limiting factor on one end of the gradient, and soil salinity at the other end. The midposition of the gradient was the most productive, but not significantly so in all years.

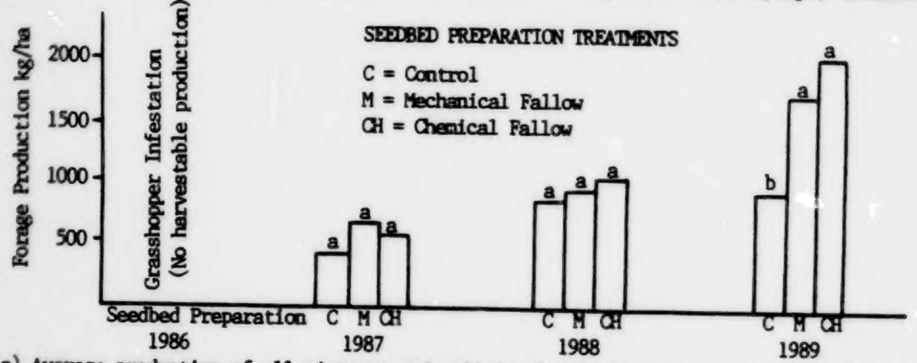
The composition of individual species changed from year to year, and in some cases, changed considerably along the salinity gradient. It was virtually impossible to identify the individual species in 1986 because of the severe damage inflicted by grasshoppers. In 1987, every species was well represented in the mixtures except for tall fescue. The dominant species was 'Pryor' slender wheatgrass (approximately 60% of the total), which was the only species that headed out. Strawberry clover had excellent emergence in 1986, but began to die out by that fall at the dry end of the gradient, and totally died out by mid-1987. In 1988, slender wheatgrass still made up 15 to 75% of the total composition (table 4). Tall wheatgrass and Altai wildrye exhibited the largest increase in plant density.

Table 4. Estimated percentage of plant composition in each mixture over all site preparation treatments at the Stillwater Saline Seep in 1988.

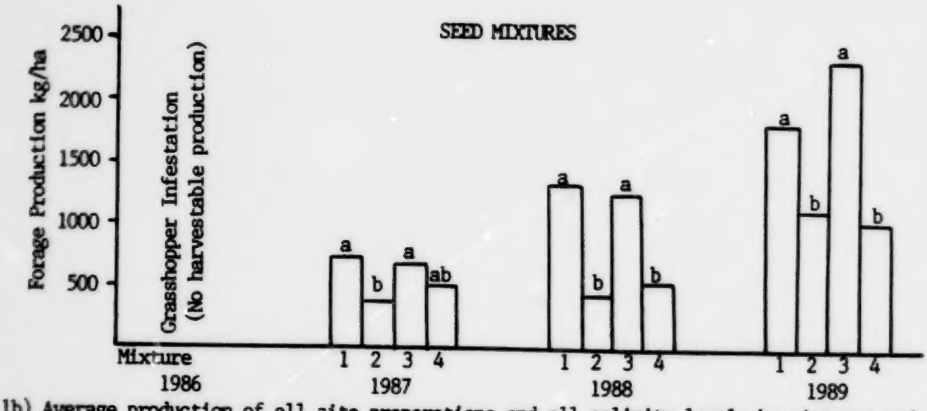
	Mix 1		Mix 2		Mix 3		Mix 4	
Gradient Extremes:	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Pryor slender wheatgrass	25	40	75	60	15	30	-	-
Jose tall wheatgrass	40	25	-	-	40	30	-	-
Prairieland Altai wildrye	30	30	-	-	25	20	80	60
Kenmont tall fescue	0	0	0	0	-	-	-	-
Shoshone beardless wildrye	5	5	10	20	-	-	20	40
Vinall Russian wildrye	-	-	-	-	20	20	-	-
Garrison creeping foxtail	-	-	15	20	-	-	-	-
9005617 strawberry clover	-	-	-	-	-	-	0	0

By 1989 the plant diversity in most of the mixtures was reduced to one or two species, and in some cases the dominance changed from one end of the salinity gradient to the other (table 5). Mixtures 1 and 3 were totally dominated by tall wheatgrass. The Altai wildrye had

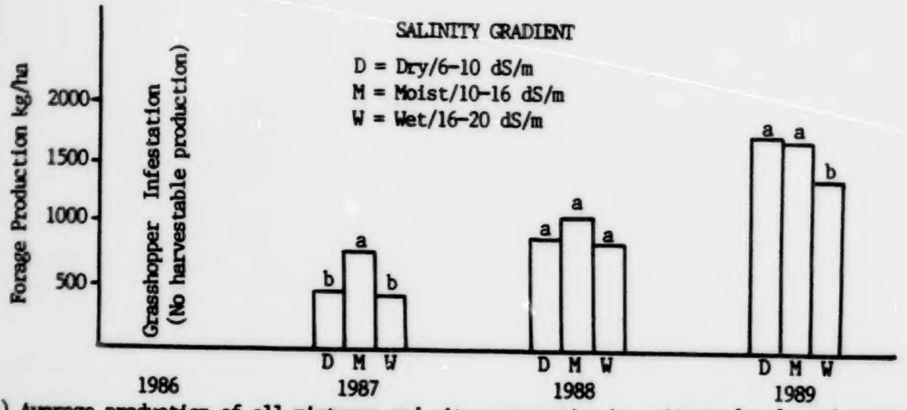
Figure 1. Forage Production[1] at the Stillwater Saline Seep Test Area, Rapelje, Montana.



1a) Average production of all mixtures and salinity levels by site preparation and years.



1b) Average production of all site preparations and all salinity levels by mixtures and years.



1c) Average production of all mixtures and site preparation by salinity levels and years.

1/ Forage production with the same letter (each year considered separately) are not significantly different at the P=.05 probability level using the LSD method of mean comparison.

diminished considerably wherever it was in competition with tall wheatgrass. Russian wildrye exhibited excellent stands on dry saline areas on other plantings when it was planted by itself, but in a mixture with tall wheatgrass, it had poor performance. As expected, the short-lived slender wheatgrass has gone from a 60 to 70% composition in 1987 to a 5 to 20% in 1989. In Mixture 2, Shoshone beardless wildrye dominates on the drier end of the gradient, while Garrison creeping foxtail survives only on the most favorable soil moisture conditions. In Mixture 4, altai wildrye dominates the dry end of the gradient, while beardless wildrye dominates the wet-saline end.

Table 5. Estimated percentage of plant composition of each seed mixture across a moisture/salinity gradient at the Stillwater Saline Seep in 1989.

	Control			Mechanical			Chemical		
	D	M	W	D	M	W	D	M	W
	1/	1/	1/	1/	1/	1/	1/	1/	1/
Mix 1									
Tall wheatgrass	100	100	100	80	90	100	80	80	90
Slender wheatgrass	0	0	0	20	10	0	20	20	10
Beardless wildrye	0	0	0	0	0	0	0	0	0
Altai wildrye	0	0	0	0	0	0	0	0	0
Tall fescue	0	0	0	0	0	0	0	0	0
Mix 2									
Beardless wildrye	90	20	75	90	20	20	10	10	0
Slender wheatgrass	10	60	0	10	10	10	70	20	20
Creeping foxtail	0	20	25	0	70	70	20	70	80
Tall fescue	0	0	0	0	0	0	0	0	0
Mix 3									
Tall wheatgrass	65	60	40	50	85	90	75	90	80
Russian wildrye	25	15	60	30	0	0	0	0	10
Slender wheatgrass	5	20	0	10	10	10	20	10	10
Altai wildrye	5	5	0	10	5	0	5	0	0
Mix 4									
Altai wildrye	60	60	0	50	20	10	80	80	20
Beardless wildrye	40	40	100	50	80	90	20	20	80
Strawberry clover	0	0	0	0	0	0	0	0	0

1/ D=dry/6-10 dS/m, M=moist/10-16 dS/m, W=wet/16-20 dS/m.

There is every indication that tall wheatgrass and Russian wildrye are probably best planted alone. Tall wheatgrass is quick to establish and, in this study, totally dominated three to four other species in a mix. Other mixtures are more compatible, and each species has the ability to dominate a particular site it is adapted to, while being a minor component of a stand on other sites. Although this study experienced several drought years, species like Shoshone beardless wildrye and Garrison creeping foxtail were still present. Had the soil moisture been more favorable, these species would play a larger role in revegetating this saline seep discharge area.

Fertilization Trial

Soil salinity can affect plant growth and productivity by decreasing water availability, acting as a toxic agent, or creating nutrient imbalances or deficiencies. Forage grasses that were established on wet-saline soils at the Bridger PMC produced a flush of growth the first 2 to 3 years, but the productivity and plant vigor rapidly deteriorated thereafter. The yellow-green coloration, particularly in beardless wildrye, suggested the possibility of nutrient deficiencies. Langdale and Thomas (1971) found that forage and protein yields of coastal bermudagrass *Cynodon dactylon* (L.) Pers. grown on moderately saline soils were enhanced by a nitrogen fertilization-soil salinity interaction possibly associated with the cation-anion balance. Ford et al. found fairway crested wheatgrass *Agropyron cristatum* (L.) Gaertn. ssp. *pectinatum* (Bieb.) Tzvel., growing in saline soils, to be stimulated primarily by nitrogen.

Methods and Materials

A study was established to evaluate the forage and seed production response of five accessions of beardless wildrye to four levels of nitrogen fertilization. Because a soil salinity gradient existed in two directions, a 5 X 5 Latin square design was used. Superimposed over the Latin square design were four nitrogen fertilization treatments in a strip-block configuration. Ammonium nitrate (34-0-0) was applied at rates of 0, 56, 112, and 168 kg ha^{-1}. The trials were established on wet-saline soils with electrical conductivity ranging from 10 to 24 dS/m^{-1}. The accessions of beardless wildrye were: Shoshone (Wyoming), P-15593 (Wyoming), P-2741 (Washington), C-77 (Colorado), and PI-314665 (Kazakstan, USSR). Seed was hand harvested from each 1 m by 3 m plot, and forage was harvested with a flail plot harvester. Plots were grown 2 years before the fertilizer treatment was applied to allow for the plots to establish uniformly.

Results and Discussion

During the 4-year fertilization period, the average forage production of all accessions with 0, 56, 112, and 168 kg N ha^{-1} produced 2,550, 4,380, 6,690, and 7,990 kg ha^{-1}, air-dried forage, respectively. A response curve of all years' average production and all accessions (Eq. [1]) indicates an average forage production increase of 38 kg ha^{-1} for each kg N ha^{-1} applied for the first 56 kg ha^{-1} of fertilizer. Forage increases of 33 and 28.5 kg ha^{-1} for each kg N ha^{-1} were realized with increases to 112 and 168 kg ha^{-1}, respectively.

$$\text{Forage Production(kg ha}^{-1}\text{)}=2477+403(\text{N rate})-0.0423(\text{N rate})^2,\ r^2=.99 \quad [1]$$

Average seed production significantly increased with increasing rates of nitrogen. Average seed production (3 years) for all accessions with 0, 56, 113, and 168 kg N ha^{-1} was 153, 303, 329, and 371 kg ha^{-1}, respectively. A response curve of all productive years for all accessions (Eq. [2]) shows an average seed production increase of 2.2 kg ha^{-1} for each kg N ha^{-1} applied for the first 56 kg N ha^{-1}. Seed production increased 1.2 and 0.25 kg ha^{-1} for each kg N ha^{-1} with fertilizer rates of 112 and 168 kg ha^{-1}, respectively.

$$\text{Seed Production(kg ha}^{-1}\text{)}=160+2.66(\text{N rate})-0.0086(\text{N rate})^2,\ r^2=0.96 \quad [2]$$

It appears that the increasing forage production has an inverse effect on seed production at higher nitrogen rates. Although seed production usually would not be attempted on strongly saline soils, this study suggests that seed production is possible with 50 to 112 kg N ha^{-1}. At higher nitrogen rates, forage production continues to increase at the expense of seed production.

Individual-year response curves show a curvilinear response to nitrogen fertilization, and the trend over time shows increasing production (both seed and forage) for 2 to 3 years, followed by a rapid decline as the stand matures (figures 2 and 3). This pattern of production is typical of most cool-season grasses grown for seed production. Although higher productivity is realized with increasing nitrogen, the forage peaked in 3 years, with fertilization and seed production peaking in 2 years.

Summary

The salt-tolerance trials at the Bridger PMC have further documented the salt tolerance of released cultivars commonly used on saline soils in the Northern Great Plains Region, i.e., tall wheatgrass (all cultivars), Russian wildrye (all cultivars), slender wheatgrass (Revenue), and Altai wildrye (Prairieland). This work has thus far resulted in two releases: Shoshone beardless wildrye and Pryor slender wheatgrass. Species presently in advanced stages of evaluation are plains bluegrass, alkali bluegrass, alkali sacaton, Nuttall alkaligrass, Gardner saltbush, strawberry clover, and Ruby Valley pointvetch.

Mixture trials have shown that tall wheatgrass and Russian wildrye do best in a monoculture, as they are too competitive with other species. Species such as slender wheatgrass, beardless wildrye, Altai wildrye, and creeping foxtail remain in a mixture, but vary their composition as soil moisture and salinity vary. Slender wheatgrass is a rapidly developing, but short-lived perennial, which can best be utilized for quick stabilization and cover. It does not maintain itself for much more than 4 years.

Nitrogen fertilization of forage grasses (particularly beardless wildrye) on saline soil will produce a significant increase in forage and seed production. Forage of beardless wildrye was still increasing at a near-linear level with 168 kg N ha^{-1}. Many of the salt-tolerant forage species will maintain themselves on saline soils, but to realize an economic return from a forage crop, supplemental nitrogen may be required.

Literature Cited

1. Berstein, Leon. 1964. Salt tolerance of plants. Agriculture Research Service. Agric. Information Bull. No. 283. Washington, DC.
2. Borrelli, John, and Don Brosz. 1983. Effects of soil salinity on crop yields. Agric. Exp. Sta. Bull. 803. Univ. of Wyoming, Laramie, WY.
3. Dewey, Douglas R. 1960. Salt tolerance of twenty-five strains of *Agropyron*. Agron. J. 52:631-635.
4. Ford, R. H., F. H. Siddoway, and R. L. Black. 1974. Forage response fertilizer on saline soils. Montana Farmer-Stockman 61(16):18-20.
5. Forsberg, D. E. 1953. The response of various forage crops to saline soils. Can. J. Agric. Sci. 33:542-549.
6. Greub, L. J., P. M. Drolsom, and D. A. Rohweder. 1985. Salt tolerance of grasses and legumes for roadside use. Agron. J. 77:76-80.

7. Holm, H. M. 1983. Soil salinity--a study in crop tolerances and cropping practices. Saskatchewan Agric., Plant Ind. Branch, Regina, Canada.
8. Hughes, T. D., J. D. Bulter, and G. D. Sanks. 1975. Salt tolerance and suitability of various grasses for saline roadsides. J. Environ. Qual. Vol. 4, No. 1, pp. 65-68.
9. Kilcher, M. R., R. W. Lodge, D. H. Heinrichs, and J. B. Campbell. 1956. Pasture and hay crops for the southern Canadian prairies. Can. Dept. Agric. Publ. 980.
10. Langdale, G. W., and J. R. Thomas. 1971. Soil salinity effects of absorption of N, P, and protein synthesis by coastal bermudagrass. Agron. J. 63:708-711.
11. Maas, E. V., and G. J. Hoffman. 1977. Crop salt tolerance--current assessment. J. Irrigation and Drainage Div., ASCE., Vol. 103, No. IR2, Proc. Paper 12993, pp. 115-134.
12. McElgunn, J. D., and T. Lawrence. 1973. Salinity tolerance of altai wildrye and other forage grasses. Can. J. Plant Sci. 53:303-307.
13. Palmer, J., D. L. Becker, and S. R. Chapman. 1968. Salinity tolerance studies in Russian wildrye (*Elymus junceus*). Proc. Mont. Acad. of Sci. 28:0-27.
14. Rauser, W. E., and W. L. Crowle. 1963. Salt tolerance of Russian wild ryegrass in relation to tall wheatgrass and slender wheatgrass. Can. J. Plant Sci. 43:397-407.

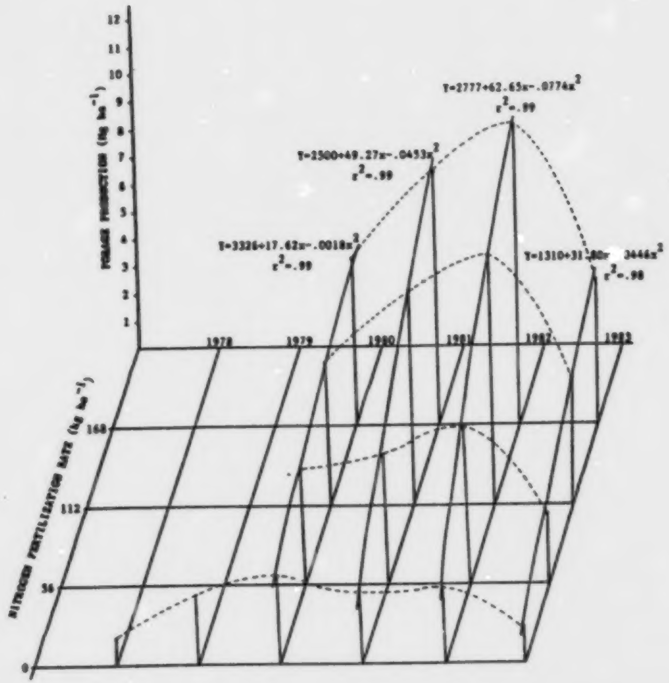


Fig. 2. Response curves showing forage production response of beardless wildrye to increasing levels of N fertilizer over a 6-year period on wet-saline soils at the Bridger PMC.

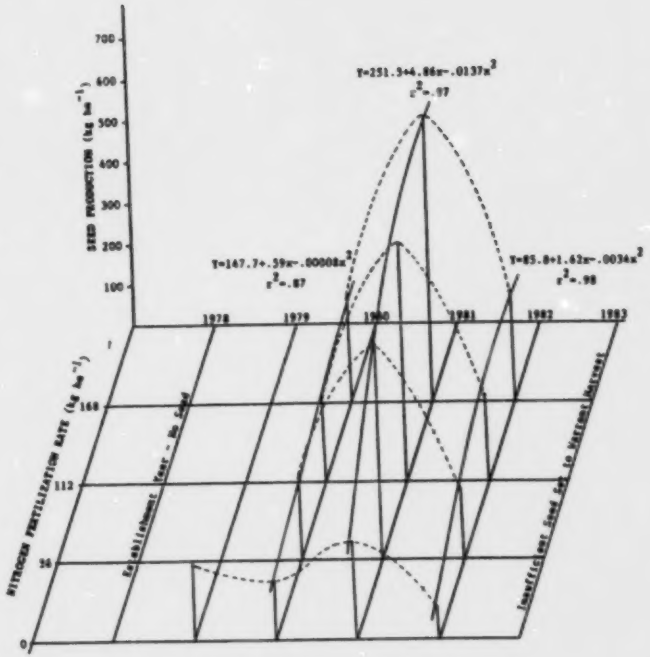


Fig. 3. Response curves showing seed production response of beardless wildrye to increasing levels of N fertilizer over a 6-year period on wet-saline soils at the Bridger PMC.

Appendix A. Species planted in Initial Evaluation Plantings on wet-saline soil at the Bridger PMC.

Genus & Species	Common Name	Genus & Species	Common Name
Grass and Grasslike			
Aeluropus litoralis	shore elurope	Elymus karataviensis	-
Agropyron cristatum	crested wheatgrass	Elymus lanceolatus	thickspike wheatgrass
Agropyron sibiricum	Siberian wheatgrass	Elymus lanceolatus lanceolatus	streambank wheatgrass
Agrostis alba	redtop	Elymus multicaulis	-
Agrostis palustris	creeping bent	Elymus riparius	riverbank wildrye
Agrostis stolonifera	carpet bent	Elytrigia pseudorepens	false quackgrass
Alopecurus arundinaceus	creeping foxtail	Elytrigia pungens	stiffleaf quackgrass
Alopecurus pratense	meadow foxtail	Elytrigia repens	quackgrass
Andropogon gerardii	big bluestem	Elytrigia smithii	western wheatgrass
A.gerardii paucipilus	sand bluestem	Festuca arizonica	Arizona fescue
Arrhenatherum elatius	tall oatgrass	Festuca arundinacea	tall fescue
Beckmannia syzigachne	American sloughgrass	Festuca elatior	meadow fescue
Bouteloua curtipendula	sideoats grama	Festuca longifolia	hard fescue
Bromus biebersteinii	meadow brome	Festuca rubra	red fescue
Bromus inermis	smooth brome	Glyceria grandis	American mannagrass
Bromus pumpellianus	pumpelly brome	Hilaria jamesii	galleta
Bromus riparius	riverbank brome	Hordeum brachyantherum	meadow barley
Buchloe dactyloides	buffalograss	Leymus angustus	Altai wildrye
Calamovilfa longifolia	prairie sandreed	Leymus arenarius	European dunegrass
Carex eleocharis	threadleaf sedge	Leymus cinereus	basin wildrye
Dactylis glomerata	orchardgrass	Leymus mollis	common dune wildrye
Danthonia parryi	Parry oatgrass	Leymus racemosus	mammoth wildrye
Deschampsia cespitosa	tufted hairgrass	Leymus salinus	salina wildrye
Distichlis spicata	inland saltgrass	Leymus trachycaulus	slender wheatgrass
Elymus canadensis	Canada wildrye	Leymus trachycaulus X Hordeum jubatum	slender wheatgrass X foxtail barley hybrid
Elymus dahuricus	Dahurian wildrye	Leymus triticoides	beardless wildrye
Elymus dasystachys	thickspike wildrye	Lolium perenne	perennial ryegrass
Elymus glaucus	blue wildrye	Muhlenbergia montana	mountain muhly
Elymus hirtiflorus	Wyoming wildrye		

Appendix A. Species planted in Initial Evaluation Plantings on wet-saline soil at the Bridger PMC. Continued.

Genus & Species	Common Name	Genus & Species	Common Name
Muhlenbergia porteri	bush muhly	Puccinellia fasciculata	Torrey alkaligrass
Muhlenbergia wrightii	spike muhly	Puccinellia festucaeformis	-
Oryzopsis hymenoides	Indian ricegrass	Puccinellia rupestris	British alkaligrass
Oryzopsis miliacea	smilo ricegrass	Schizachyrium scoparium	little bluestem
Panicum virgatum	switchgrass	Scirpus robustus	saltmarsh bulrush
Phalaris arundinacea	reed canarygrass	Setaria italica	foxtail bristlegrass
Phalaris canariensis	common canarygrass	Setaria viridis	green bristlegrass
Phleum pratense	timothy	Sorghastrum nutans	yellow indiangrass
Poa ampla	big bluegrass	Spartina alterniflora	smooth cordgrass
Poa arida	plains bluegrass	Spartina gracilis	alkali cordgrass
Poa glaucantha	upland bluegrass	Spartina patens	marshhay cordgrass
Poa glaucifolia	swallen bluegrass	Spartina pectinata	prairie cordgrass
Poa juncifolia	alkali bluegrass	Sporobolus airoides	alkali sacaton
Poa longifolia	longleaf bluegrass	Sporobolus cryptandrus	sand dropseed
Poa nevadensis	Nevada bluegrass	Stipa comata	needleandthread grass
Poa pratensis	Kentucky bluegrass	Stipa viridula	green needlegrass
Psathyrostachys juncea	Russian wildrye	Stipa X Oryzopsis	Mandan ricegrass
Pseudoroegneria spicata		Thinopyrum intermedium	intermediate wheatgrass
inermis	beardless wheatgrass	T.intermedium barbulatum	pubescent wheatgrass
Puccinellia airoides	Nuttall alkaligrass	Thinopyrum ponticum	tall wheatgrass
Puccinellia capillaris	-	Tripsacum dactyloides	eastern gamagrass
Puccinellia distans	weeping alkaligrass		
Legumes			
Astragalus agrestis	field milkvetch	Astragalus semibicularis	-
Astragalus cicer	cicer milkvetch	Astragalus striatus	prairie milkvetch
Astragalus falcatus	sicklepod milkvetch	Coronilla varia	common crownvetch
Astragalus flexuosus	flexile milkvetch	Dalea candida	slender white prairieclover
Astragalus galegiformis	tall milkvetch		
Astragalus onobrychis	-	Dalea purpurea	purple prairieclover

Appendix A. Species planted in Initial Evaluation Plantings on wet-saline soil at the Bridger PMC. Continued.

Genus & Species	Common Name	Genus & Species	Common Name
Glycyrrhiza lepidota	American licorice	Salicornia europaea	marshfire glasswort
Hedysarum boreale	northern sweetvetch	Salicornia fruticosa	leadbush glasswort
Kochia prostrata	prostrate summercypress	Salicornia perennis	woody glasswort
Iliamna grandiflora	wild hollyhock	Salicornia pusilla	-
Lathyrus ochroleucus	cream peavine	Salicornia ramosissima	bush seepweed
Lathyrus latifolius	perennial peavine	Sanguisorba minor	small burnet
Lathyrus tingitanus	Tangier peavine	Stachys olympica	lambears
Lathyrus tuberosus	groundnut peavine	Suaeda maritima	sea seepweed
Lotus corniculatus	birdsfoot trefoil	Swainsonia salsula	Swainson pea
Medicago falcata	yellowflowered alfalfa	Trifolium fragiferum	strawberry clover
Medicago sativa	alfalfa	Trifolium hybridum	alsike clover
Melilotus alba	white sweetclover	Trifolium lupinaster	lupine clover
Onobrychis viciifolia	sainfoin	Trifolium pratense	red clover
Oxytropis riparia	Ruby Valley pointvetch	Triglochin maritima	seaside arrowgrass
Penstemon jamesii	James penstemon	Vicia americana	American vetch
Penstemon palmeri	Palmer penstemon	Vicia cracca	bird vetch
Salicornia dalichostachya	-	Vicia tenuifolia	bramble vetch
Shrubs			
Artemisia cana	silver sagebrush	Atriplex rosea	tumbling orach
Artemisia nova	black sagebrush	Atriplex semibaccata	Australian saltbush
Artemisia tridentata	big sagebrush	Atriplex suberecta	-
Atriplex canescens	fourwing saltbush	Ceratoides lanata	winterfat
Atriplex canescens aptera	fourwing saltbush	Cercocarpus ledifolius	curlleaf mountainmahogany
Atriplex confertifolia	shadscale	Chrysothamnus nauseosus	rubber rabbitbrush
Atriplex halimus	Mediterranean saltbush	Halimodendron halodendron	Siberian salttree
Atriplex hortensis	garden orach	Rhus trilobata	skunkbush sumac
Atriplex lentiformis	big saltbush	Salvia carnosa	desert sage
Atriplex leptocarpa	-	Salvia pitcheri	pitcher sage
Atriplex muelleri	-	Sarcobatus vermiculatus	greasewood
Atriplex nuttallii	Gardner saltbush	Shepherdia argentea	silver buffaloberry
Atriplex pseudocampanulata	-	Yucca glauca	small soapweed

SIMULATED SOIL EROSION AND CROP PRODUCTIVITY

A. Kapoor and C.F. Shaykewich
Department of Soil Science
University of Manitoba
Winnipeg, Manitoba R3T 2N2

ABSTRACT

Several different soil types were employed to study the effects of simulated soil erosion on wheat and canola productivity. Varying amounts of topsoil were scraped from the surface of experimental fields and crops were grown using three levels of fertilizer applications. Topsoil removal treatments included 0 cm removed, (a basis for comparison), 5, 10, and 20 cm of topsoil removed. Fertilizer application treatments consisted of no fertilizer applied, recommended rate of fertilizer applied and approximately double the recommended rate. Crops utilized for this study were Columbus wheat and Westar canola. It was found that yields generally decreased as the amount of topsoil removed increased. Data indicated yields to be severely depressed on all topsoil removal treatments where no fertilizer was applied. Soil texture played a role in determining the outcome of yields in that on the coarse textured soils, even twice the recommended rate of fertilizer was not able to bring the yields back to that of the control. The recommended rate of fertilizer application was able, on the other hand, to mitigate topsoil losses on the fine textured soils and in some cases yields exceeded the control at twice the recommended rate of fertilizer.

Introduction

Soil erosion is a natural ongoing process that, with the influence of man, is accelerating to heights that can threaten our potential productivity. It has been well documented that crops grown on eroded soils will yield lower than crops grown on uneroded soils. This loss in productivity is due to a loss in fertility and because of the other changes that occur due to soil erosion. To elaborate, soil erosion is responsible for losses of vital soil nutrients, losses of soil organic matter, a decrease in the water holding capacity, changes in the soil structure and soil texture, a root zone depletion and exposure of the subsoil, all generally adverse changes in the soil indicative by the loss in productivity.

Much research has been done to determine productivity losses due to erosion. Langdale et al. (1979) found that a loss of 15 cm of topsoil from a Southern Piedmont soil resulted in a 42% reduction in corn yields. Battiston et al. (1987), studying yields on eroded and uneroded sites, found the eroded sites yielded on average only 59% of that on noneroded areas. A study using simulated soil erosion was conducted by Tanaka and Aase (1989). They found that removal of 0.06, 0.12 and 0.18 m of topsoil reduced spring wheat yields an average of 9, 28 and 45% compared to the 0.00 m soil removal treatment. Such results make clear the need to look seriously at the control of soil erosion.

To date the best way to study the effect soil erosion has on crop productivity is by simulating soil erosion. The objective of this study was to examine the losses in productivity due to erosion by scalping the soil surface to different depths as a means of simulating erosion.

Materials and Methods

Six field sites were developed in Manitoba. Soil texture varied and included a Pembina clay loam, a Ryerson fine sandy loam, a Reinland loamy very fine sand, a Newdale clay loam, a Willowcrest fine sand and a Waskada very fine sandy clay loam.

Two sites were 0.33 ha in total area and four sites were 0.71 ha. The sites were set up in a completely randomized split plot design with pathways both within and among treatment plots. Four topsoil removal treatments, 0, 5, 10, and 20 cm and three fertilizer regimes 0, recommended rate based on fall soil tests, and approximately double the recommended rate constituted the main plot and the subplot treatments respectively. Each topsoil removal treatment was replicated four times resulting in 48 observations from each site.

Seed bed preparation was done according to conventional farming methods. Nitrogen, sulfur and potassium fertilizers were hand broadcast to appropriate subplots and disced down for good incorporation before seeding. The recommended rate of phosphorus was added with the seed and for double the recommended rate treatments, half was seed placed and the other half was drilled in below the seed. Seeding of Columbus wheat in year one, two and five and Westar canola in years three, four and six and appropriate field maintenance including necessary weed control was accomplished by conventional methods.

Crop emergence was tabulated to assess potential differences due to treatment differences. The general conditions of plants was constantly monitored to correlate specific plant conditions with respect to treatments. Rainfall was recorded with recording rain gauges and volumetric rain gauges and where incomplete due to equipment malfunction, information was obtained from Atmospheric Enviroment stations located closest to the research plots.

Soil Analyses

Physical soil analyses of the experimental soils included bulk density, field capacity, permanent wilting point, available moisture and particle size analysis. Chemical analyses of the soils consisted of pH and conductivity determinations, nitrate-nitrogen determinations, available phosphorus determinations, exchangeable potassium, sulfate-sulfur, organic matter content and sulfur concentrations.

Plant Analyses

Midseason tissue analyses for nitrogen, phosphorus, potassium and sulfur were conducted on the ground tissue of ten randomly selected plants from each subplot. From the final yield samples, tissue analyses on the straw was conducted to determine nitrogen, phosphorus, potassium and sulfur content. In the case of canola, oil and protein content of the seed was determined and for wheat, the nutrient content of the seed was examined.

Yields

Yields were determined by sampling one random representative square meter from within each subplot for the first four years. In the last two years, to decrease the level of error, two randomly chosen square meters from each subplot were selected. Yields were determined and an average for each subplot was calculated.

Results and Discussions

Crop Emergence

Crop emergence was monitored because it has been documented (Hirch 1984) that crust strengths of eroded soils increased as the level of topsoil removal increased. In this case of simulated erosion, removing topsoil unselectively, no differences in emergence of the subplots were observed. Topsoil removal did not significantly impede the emergence of wheat or canola seedlings.

Crop Conditions

Soon after emergence, it was evident that distinctly different growth stages were present among the treatments. Where no fertilizer was added, growth of the plants was slower, development was retarded, stems were thinner and plants were a pale green color. The condition worsened as the amount of topsoil removed increased. Where plots had been fertilized, the plants were developing more rapidly, grew thicker stems and donned a darker more healthy looking green color. As a rule, plants grown with the recommended rate of fertilizer and those grown with double the recommended rate, rarely showed any significant visual differences.

Midseason Plant Analysis

Ten random plants were selected from each subplot and nutrient analyses was conducted on the dry, ground samples. Where no fertilizer was added, nutrient content was a bit lower than where fertilizer was added however, there were no statistically significant differences among treatments.

Straw Productions

It was found that adding fertilizer to the various topsoil removal treatments increased the amount of straw produced. This is of great significance because an increase in straw returned to the soil, increases the nutrients added to the soil and also increases the soil surface cover. This in turn reduces the amount of erosion that can occur.

Final Harvest

It was found that yields were reduced as the level of topsoil removed increased. With fertilizer additions yields were increased with fine textured soils responding best. In some cases, the recommended rate of fertilizer was able to bring the yields above the control of no topsoil removed and no fertilizer added. In fine textured soils the additions of fertilizer were better able to overcome the loss of topsoil. The recommended rate of fertilizer was able to bring yields back to that of the control. Twice the recommended rate did not significantly increase yields further (Figure 1).

In coarse textured soils, the mitigating effects of fertilizer were not as great. Yields were raised to the level of the control but not until double the recommended rate of fertilizer had been added (Figure 2). This indicated that nutrient deficiencies could be overcome, although production costs will be considerably increased. In the Willowcrest, the coarsest soil, the results showed that fertilizer was even less effective in restoring yields. Even at twice the recommended rate of fertilizer, yields were severely depressed as topsoil removal increased (Figure 3). The loss of topsoil results in the loss of yields which fertilizer additions can not restore. Massee and Waggoner (1985) also found that reductions in yields due to the removal of 15 cm of topsoil could not be restored by additions of fertilizer. Where yields were not increased despite the large fertilizer applications, it is assumed that some factor other than fertility is reducing productivity.

In summary, it was found that simulated erosion resulted in productivity losses. Fine textured soils responded better to fertilizer applications than coarse textured soils. In some cases, even double the recommended rate of fertilizer was not able to overcome the losses of topsoil, clearly indicating that factors other than nutrient losses are responsible for productivity losses due to erosion. Further study of the actual changes to the soil that occur due to soil erosion may elucidate the cause of the loss in productivity observed in this experiment.

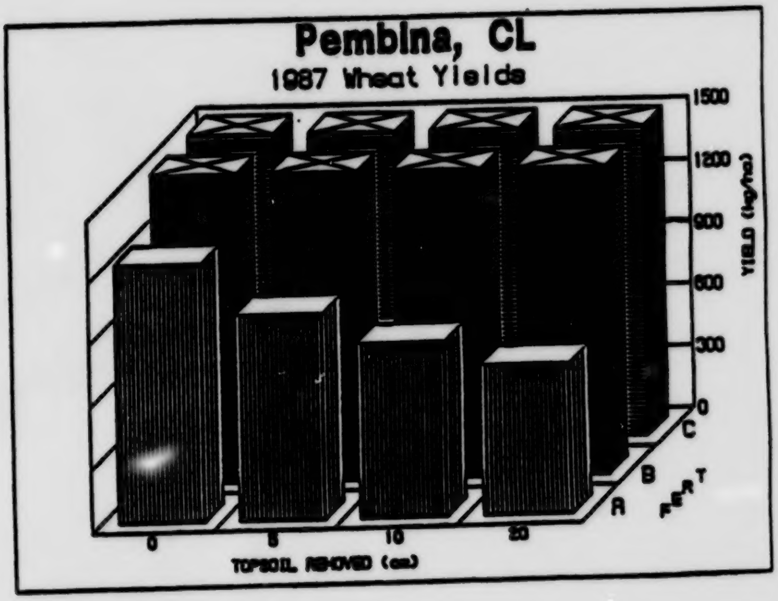


Figure 1. Effect of topsoil removal and fertilizer applications on wheat yields grown on a Pembina clay loam.

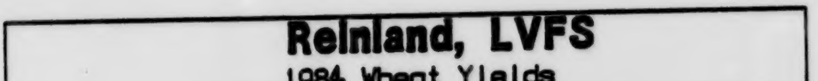


Figure 2. Effect of topsoil removal and fertilizer applications on wheat yields grown on a Reinland loamy very fine sand.

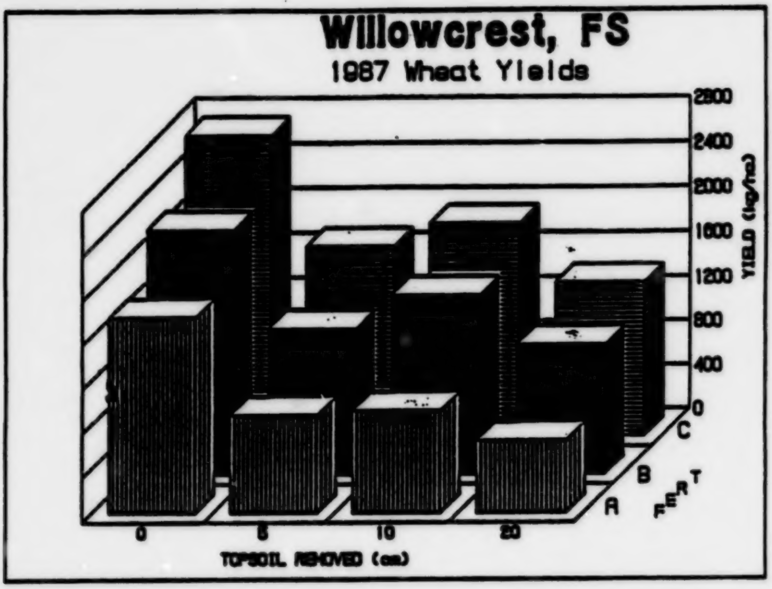


Figure 3. Effect of topsoil removal and fertilizer applications on wheat yields grown on a Willowcrest fine sand.

References

Battiston, L.A., M.H. Miller and I.J. Shelton. 1987. Soil erosion and corn yield in Ontario. I. Field evaluation. Can. J. Soil Sci. 67:731-745.

Hirch, L. 1984. Soil crust strength and the emergence of rapeseed. Bachelor of Sci. in Agric. Thesis, Dept. of Soil Sci., University of Manitoba.

Langdale, G.W., J.E. Box, Jr., R.A. Leonard, A.P. Barnett, and W.G. Fleming. 1979. Corn yield reduction on eroded Southern Piedmont soils. J. Soil and Water Conserv. 34:226-228.

Massee, T.W. and O. Waggoner. 1985. Productivity losses from soil erosion on dry cropland in the intermountain area. J. Soil and Water Conserv. 40:447-450.

Tanaka, D.L. and J.K. Aase. 1989. Influence of topsoil removal and fertilizer applications on spring wheat yields. Soil Sci. Soc. Am. J. 53:2[illegible]8-232.

AN ASSESSMENT OF THE ALTERNATE LAND USE PROGRAM FOR EROSION CONTROL OF STEEP SLOPED LAND ALONG THE RIDING MOUNTAIN ESCARPMENT

W. Hildebrand and V. D'Angiolo
Whitemud Watershed Conservation District, Neepawa, Manitoba

INTRODUCTION

The steep slopes of the Riding Mountain Escarpment are a unique physiographic feature of Manitoba. The Riding Mountains rise some 370 meters above the Manitoba Lowlands to the east. These steep slopes present special land use challenges, in particular, the prevention of water erosion.

The Rural Municipality of Rosedale encompasses the eastern slopes of the Riding Mountain. As settlement in this region continued from the turn of the century, large acreages of land were cleared of trees for agricultural use. Much of the deforested steep sloped land was marginal and extremely prone to erosion by surface water runoff. The severity of the erosion problem was evident as early as 1957 when the Riding Mountain - Whitemud Watershed Committee was formed to find ways to prevent the erosion.

By 1966, the Rosedale Municipal Council realized the impacts of soil erosion were far broader than the loss of topsoil. In a plea for assistance to the Federal and Provincial governments, the rural council highlighted their concerns:

1. Due to past and present land use, erosion and gullying on the eastern slopes of the Riding Mountain has accelerated yearly, destroying the productive base and reducing farm incomes.

2. With the loss of topsoil, the land assessment within the area has been reduced. At the same time, service costs for road and crossing washout repairs and drain maintenance have increased, placing the area in a deficit position.

3. The rapid runoff is the source of damage at the base of the escarpment including the siltation of drains, shale deposition, and erosion and flooding on productive land.

4. The area is the origin of the headwaters of many streams which flow into the Whitemud River. Consequently, flooding and shale deposition problems affect neighboring municipalities and the entire Whitemud Watershed.

5. With the destruction of the productive soil base the younger generation have no prospects of a livelihood and are forced to leave the district. Many of the older residents are facing decreasing returns from farms which are depreciating in value.

A meeting was arranged between the municipal council and members of the Federal and Provincial governments to develop a plan to address these problems. The result of the meetings was the development of the Alternate Land Use (A.L.U.) program in 1967. Through Federal and Provincial funding the A.L.U. program proposed to purchase by voluntary sale the severely eroded parcels of land within the Rural Municipality of Rosedale. The majority of these lands would be seeded down to forage cover while very steep areas would be replanted to trees. A soil conservation demonstration farm would be established in the area to demonstrate conservation farming practices that were economically realistic. The A.L.U. land acquisition program was carried out from 1972 to 1977. During this time some 10,000 hectares or 156 quarter sections of land were purchased and converted to alternate land management.

OBJECTIVES

The objective of this paper is to examine the history and effectiveness of the A.L.U. program. In particular, did it reduce erosion and encourage soil conservation practices along the Riding Mountain escarpment? Further did A.L.U. land management practices reduce flooding, stream sedimentation and shale deposition at the base of the escarpment?

STUDY AREA

The A.L.U. program was implemented in the Rural Municipality of Rosedale located in south-central Manitoba approximately 200 kilometers west of Winnipeg. The study is bounded to the north by the village of Kelwood, east by Highway 5, south by P.R. 265 and west by the R.M. of Rosedale's western boundary.

METHODS

A combination of methods were utilized. These included:

1. A questionnaire survey of 20 farmers including those whose land was eroded and purchased in the A.L.U. program as well as landowners at the base of the escarpment who experienced flooding and erosion. The questionnaire included 53 open ended questions.

2. Soil conservation professionals involved in the initiation and implementation of the A.L.U. program were interviewed.

3. Land use changes were assessed by comparing aerial photographs on 10 quarter sections of A.L.U. lands for the years 1958, 1964 and 1981. Extensive ground proofing was completed on these quarter sections to compare current land use with land management recommendations prepared by Manitoba Agriculture (Slevinsky, 1977).

QUESTIONNAIRE SURVEY RESULTS AND DISCUSSION

Pre A.L.U.: The Polish and Ukrainian homesteaders cleared most of the best farm land manually prior to 1940. With the introduction of the bulldozer around 1940 additional acreages were cleared, mostly marginal land. The survey indicated very little new land had been cleared in the last ten years.

The homesteaders farmed by trial and error. The practise of summerfallow, usually on an every other year basis was most common. As expected, crop production was reported as excellent for the first ten years after breaking. Yields dropped as the rich topsoil washed off the unprotected slopes. It would only take one flash storm or quick spring thaw to erode tons of topsoil, cutting up fields and creating irreparable gullies. All resource professionals interviewed stated that the land management practices were unsuitable to the topographic and soil limitations of the area. Given the severity of the erosion, the financial constraints of the landowners, and the need for long term management, the acquisition of the eroded land was seen as the only practical solution to the erosion problem.

Land was purchased based on an assessment of its erosion damage or potential for erosion damage. The terms and conditions of the land acquisition were well understood and accepted by area farmers. The majority of farmers were satisfied with the price they received. It was indicated that most who sold land were at retirement age, their children expressed no interest in farming the eroded land and there were no other interested buyers. Given these conditions it is easy to understand why the program was so well received.

Post A.L.U.: All of the farmers interviewed agreed that the eroded land could be restored through the implementation of soil conservation programs. However, they felt government intervention was necessary as they did not have the financial resources nor the expertise to implement the programs.

Twenty years after the initiation of the A.L.U. program, ninety percent of the farmers felt the program was successful in controlling erosion. The establishment of forage crops to stabilize the steep sloped land was seen as the most beneficial program. There was total agreement that the A.L.U. program helped demonstrate the importance of implementing soil and water conservation practices as an economic priority for farming in the area. Seventy-seven percent of those surveyed felt surface water runoff and downstream flooding had been reduced as a result of the forage and block tree planting programs.

The Crown Lands Branch currently administers the A.L.U. lands which are leased to area farmers for hay. The majority of those interviewed have no complaints with the current lease system, however, seventy percent recommended the livestock grazing restriction should be removed. Most of the hay stands are 15 years old and are currently being renovated. The land is cultivated, cropped for two years and underseeded to tame hay in the second crop year.

Seventy-five percent of the producers interviewed felt A.L.U. lands should be resold to private ownership. If the lands were to be sold, eighty percent agreed land use regulations should be established to discourage inappropriate land use. None of the professionals interviewed felt the land should be sold to private interests.

AERIAL PHOTOGRAPH INVESTIGATION RESULTS AND DISCUSSION

Table 1 indicates land use changes on ten quarter sections of land from pre A.L.U. years (1958 & 1964) to 1981.

Table 1. Land Use Changes On Ten Quarter Sections Of A.L.U. Lands, 1958 to 1981 (hectares).

Year	Native Bush and Meadow	Farmsteads	Block Tree Plantations	Cereals	Forages
1958	209	12	0	452	10
1964	208	9	13	405	48
1981	205	6	61	27	384

* for conversion to acres, multiply by 2.47

The most significant land use change is the conversion of land in cereal production to forage crops. The total area planted to forages and block tree plantations through the A.L.U. program almost entirely account for the area in cereal production in 1958.

Air photos from 1958 and 1964 show extensive water erosion with deep gully formation. Cultivated hills and slopes on summerfallow show light tones indicating the lack of topsoil. Air photos from 1981 portray visible improvements in land management. The severly eroded steep slopes are completely stabilized with tree plantations and many of the gullies are contoured into grassed runways.

LAND USE RECOMMENDATION RESULTS AND DISCUSSION

Manitoba Agriculture developed land use policy guidelines for protecting escarpment soils susceptible to water erosion in the Rural Municipality of Rosedale (Slevinsky, 1977). These soils are the Granville, Waitville, Clarksville, Clarksville-Wapus, and Wapus Associations (Ehrlich et. al., 1958). Land use guidelines for these soil associations recommend soils on slopes from six percent to ten percent should be seeded to perennial forages. Soils on slopes exceeding 10% should be maintained in permanent native cover. From extensive ground proofing on the ten quarter sections of land being studied, current A.L.U. land management is ninety percent in accordance with Manitoba Agriculture land use guidelines.

CONCLUSIONS

The most important factors affecting land use on Riding Mountain escarpment soils are irregular topography and steep slopes which contribute to a serious problem of soil erosion by water. Manitoba Agriculture recommends perennial forages be seeded on moderately sloped land while steep sloped land should be maintained in permanent native cover.

The results indicate A.L.U. lands are being managed in accordance with Manitoba Agriculture recommendations. Results from the landowner survey and air photo investigation indicate the A.L.U. program has been successful in stabilizing erosion prone soils along the escarpment. It is locally accepted that flooding and sedimentation problems at the base of the escarpment have been reduced because of delayed spring runoff and increased infiltration of surface water on lands planted to forages and trees.

While the stabilization of erosion prone soils on the steep sloped land was the primary objective of the A.L.U. program, the program accomplished much more. In fact, the A.L.U. program is an excellent model of sustainable development. An alternate method of farming was introduced that was compatible with the land resource. It provided economic returns but did not damage prospects for resource use by future generations. The demonstration of soil conservation programs has provided an educational awareness and acceptability of adapting conservation farming practices throughout the area. The A.L.U. program provided additional socio-economic-ecologic benefits which would be impossible to evaluate. Overall, the A.L.U. program may well be the most successful soil conservation program implemented in the Province of Manitoba.

RECOMMENDATIONS

As a result of the investigation into the history, effectiveness and outcome of the A.L.U. program, the following land use recommendations are proposed:

1. Current A.L.U. Crown lands should not be sold to private ownership. The socio-economic-ecologic benefits of the A.L.U. program are far too important to allow a potential recurrence of erosion related problems in the future.
2. A program of land acquisition of escarpmental land and land at the base of the escarpment should be re-introduced by the Province of Manitoba to protect these fragile areas from future development.
3. The A.L.U. program should be used as a model demonstrating successful soil conservation programs for areas with erodible soils, steep slopes and irregular topography. In particular, perennial forage cover programs that prevent erosion and reduce runoff on escarpment lands should be promoted.
4. Policies should be incorporated into local planning district development plans that restrict clearing of vegetation on erosion risk lands and discourage developments that would increase soil erosion.
5. Livestock grazing leases on A.L.U. Crown land should not be approved. The Clarksville/Wapus soils complex are very erodible and when grazed become vulnerable to gully erosion as a result of cattle trails that inevitably develop.
6. Multi-purpose small dams along natural escarpmental creeks should be promoted. The dams provide water storage, trap shale, stabilize stream banks, dissipate runoff water energy, and enhance wildlife habitat.
7. New initiatives in soil and water conservation to prevent erosion should be made available to area farmers through Conservation Districts programs or other conservation groups.

LITERATURE CITED

Ehrlich, W. A., L. E. Pratt, E. A. Poyser, and F. P. Leclaire. Report of Reconnaissance Soil Survey of West Lake Map Sheet Area. Manitoba, Canada: Manitoba Dept. of Agric. 1958.

Slevinsky, L.F. Protected Area Policy For Escarpment Soils Subject to Water Erosion In The Whitemud Conservation District. Manitoba Dept. of Mines, Resources and Environmental Management, Water Resources Division, 1977.

DESIGN AND OPERATION OF THE PFRA EROSION PLOTS AT MIAMI, MANITOBA

J.M.W. Black[1], D.G. Smith[1] and W.J. Pauls[2]
[1]PFRA, Regina
[2]Department of Soil Science, University of Manitoba

ABSTRACT

PFRA installed 16 erosion plots near Miami, Manitoba during 1984-85. The primary objective of the plots is to gather information in order to test the applicability of the Universal Soil Loss Equation in southern Manitoba. The paper discusses the design and installation of the plots. It also discusses plot management and sampling procedures.

INTRODUCTION

The Universal Soil Loss Equation (USLE) was developed in the USA in order to select suitable conservation practices to control water erosion (Wischemier and Smith, 1978). The USLE estimates sheet and rill erosion from hillslopes. The equation is:

$$A = RKLSCP \qquad \text{(Equation 1)}$$

Where:
A = soil lost in units of mass/unit area
R is a rainfall factor
K is a soil erodibility factor
L is a slope length factor
S is a slope steepness factor
C is a crop cover factor
P is an erosion control factor.

Slevinsky and Shaw (1977) proposed that the USLE be adopted in Manitoba for soil conservation planning but noted that evaluation of the input factors for Manitoba conditions would be required in order to use the equation. Input factors for the USLE may be estimated using procedures detailed by Wischemier and Smith (1978), however factors estimated using these procedures may not be applicable to conditions on the Prairies (PFRA, 1982; Novak and van Vliet, 1983; Wahome and Shaykewich, 1988). The USLE must be verified and local input factors quantified before the equation can be used with any confidence on the Prairies.

Sixteen water erosion plots were established near Miami, Manitoba during 1984-5 in order to test the USLE in southern Manitoba.

The objectives of the erosion plots are:

(1) To gather and interpret data in order to test the USLE in southern Manitoba.
(2) To verify, or if necessary, modify existing adjustments of the USLE to accommodate erosion from snowmelt.
(3) To evaluate the soil erodibility (K) and crop cover (C) factors of the USLE for local soils and crop rotations.
(4) To evaluate the effects of minimum tillage on runoff and erosion from small plots.
(5) To compare and demonstrate the effects of local rotations and cropping practices on erosion and runoff.

The plots are installed on an imperfectly drained Gretna clay. The site has a southerly exposure and contains slopes from 11.3 to 12.5%. This paper discusses the design, operation and sampling methods employed on these plots.

PLOT DESIGN AND MANAGEMENT

The USLE is an empirical relationship developed from regression analysis of erosion plot data. In order to test the equation and develop local input variables, the erosion plots employ the standard dimensions used in the development of the USLE. This minimizes the assumptions required in data interpretation.

The plots are 22.1 m long and 2.7 m wide with borders to exclude offsite runoff. All plot runoff with entrained soil is collected and conveyed to collection tanks set into the ground. The collection tanks consist of 1.8 m lengths of 0.9 m diameter culvert welded longitudinally to the inside face of a similar length of 1.8 m diameter culvert and onto a common baseplate. Tanks are embedded vertically into the ground at the bottom of the plots. Runoff is conveyed into the tanks by a V shaped flume (Figure 1).

The 0.9 m diameter tanks can accommodate 18.9 mm of runoff from the plots. This is equivalent to runoff from approximately 40 mm of rain on summerfallow and 60 mm of rain from cropped plots. The 1.8 m diameter plots can accommodate 75 mm of runoff from the plots. The smaller tanks allow increased precision of measurement from smaller rainfall events. The plot design accommodates snowmelt runoff and runoff from rainfall with minimal maintenance. Both flumes and tanks are enclosed in a wooden shed to exclude direct precipitation.

After an erosion event the depth of runoff in each tank is measured and the suspension is agitated using a re-circulating pump. Triple 500 ml samples are taken from the top, middle and bottom of the suspension using a submersible electric pump. Samples are dried in an oven and the weight of soil in the suspension determined in order to calculate the loss of soil from the plot. Plots are sampled during spring runoff and after rainfall events which result in more than 0.18 m depth of solution in the 0.9 m diameter tanks. Runoff events which result in less volume of runoff contain very small quantities of sediment.

A tipping bucket raingage is used to collect rainfall intensity data. The energy/intensity data required to calculate the USLE R factor is interpreted from the raingage charts using methods described by Wischemier and Smith (1978). Vegetative cover is estimated using a calibrated rope before and after spring workdown and seeding operations, weekly during the growing season and after harvest. Cover data is used to estimate the USLE C factor.

The plots are maintained using farm equipment and similar tillage practices to those on adjoining farmland. Rotations employed on the plots are:

(1) continuous fallow (used to evaluate the USLE K factor)
(2) wheat - wheat - canola
(3) wheat - wheat - canola (minimum till).

Eight replications of the wheat - wheat - canola conventional tillage rotation are in place. Four replications of rotations 1 and 3 were employed for a total of 16 plots. Rotations were randomly allocated to the plots.

Annual tillage operations on the plots varies with the weather and soil conditions. The Gretna clay has a tendency to form large hard lumps if tilled at the wrong moisture content. Seedbed preparation on conventionally tilled plots generally requires two passes with tandem discs, or a heavy duty cultivator, and one pass with harrows. The crop is seeded with a hoe press drill. One pass with a cultivator is used after harvest. The minimum till plots receive one less preseeding tillage in the spring and no fall tillage. The summerfallow plots are tilled as necessary to kill weeds and to break up any surface crust. They generally receive six passes per season.

Plot operation commenced in 1985 which was used as a shakedown year. Wheat was grown on all but the summerfallow plots. Data from 1985 will not be reported: (a) because the plots were disturbed during installation of the aprons, (b) because a different sampling procedure was employed, and (c) due to problems with leaking collection tanks.

SAMPLING METHODS

Data from plots of this design is sensitive to the accuracy of subsampling since only 4.5 litres of suspension is analyzed out of perhaps 45 000 litres collected in the tanks. Sampling procedures were originally developed by the University of Manitoba under contract. Airdry soil from the plot area and clean water were added to a large tank and a small tank to make up seven concentrations of suspension representing soil loss of between 0.1 to 10.0 t ha^{-1}. The suspensions were agitated for 2, 5 or 10 minutes using: (a) a 1.8 m length of 76 mm diameter PVC pipe with a five hole cap at the end; (b) as (a) but with an 90 degree elbow between the pipe and the cap; (c) the 1.8 m PVC pipe with a 0.9 m length of ABS pipe attached to form a T at the end of the PVC pipe. Triplicate samples were taken at the top, middle and near the bottom of the suspension. The measured concentration of samples was correlated to the known concentration in the tank. A quadratic expression explaining 99.9% of sampling variability was obtained by agitating for five minutes before sampling using method (b) above.

The correlation coefficient was much better than expected for sampling of this nature so the calibration was repeated twice to confirm that no mistakes had been made, and to extend the range of calibration to 50 t ha^{-1} equivalent soil loss from the plots. The results from all three calibrations have been combined together in Figures 2 and 3 which again show excellent relationships. A linear correlation between the prepared concentration and the measured concentration in the large tank is shown in Figure 2. The regression equation is detailed in Figure 2 and has a coefficient of determination of 0.994 indicating that 99.4% of the variability found in the samples can be explained by the equation. The calibration for the small tank is shown in Figure 3, in this case a multiple regression relationship explains 99.6% of sample variability. Both relationships are excellent, giving considerable confidence in the sampling procedures.

REFERENCES

Novak, M.D. and Van Vliet, L.J.P. 1983. Degradation effects of soil erosion by water and wind in Soil Degradation in British Columbia. Proceedings of the eighth meeting of the British Columbia Soil Science Workshop. B.C. Ministry of Agriculture and Food, Victoria, B.C.

PFRA. 1982. Land Degradation and Soil Conservation Issues on the Canadian Prairies. Agriculture Canada, Regina, Saskatchewan. 326 pp.

Slevinski, L.F. and Shaw, G.A. 1977. Application of the Universal Soil Loss Equation in Manitoba. Proceedings of the 21st Annual Manitoba Soil Science Society Meeting. Winnipeg, Manitoba.

Wahome, E.K. and Shaykewich, C.F. 1988. Measurement of water erosion in Manitoba. Proceedings of the 31st Annual Manitoba Soil Science Meeting. Winnipeg, Manitoba.

Wischemier, W.H and Smith, D.D. 1978. Predicting rainfall erosion losses - a guide to conservation planning. USDA, Agriculture Handbook #537. 58pp.

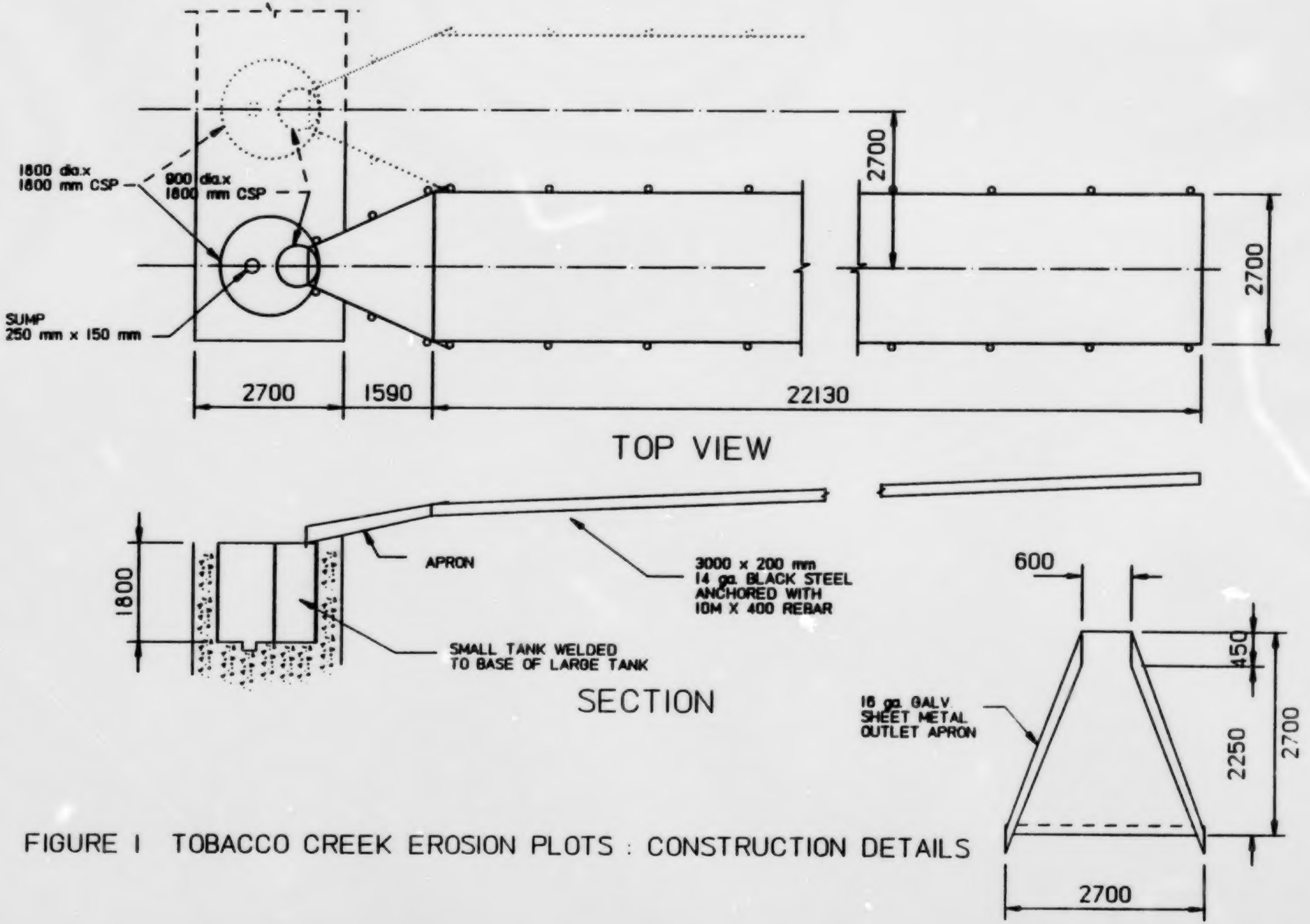

1800 dia.x
1800 mm CSP
900 dia.x
1800 mm CSP
SUMP
250 mm x 150 mm
2700
2700
2700
1590
22130
TOP VIEW
1800
APRON
3000 x 200 mm
14 ga. BLACK STEEL
ANCHORED WITH
10M X 400 REBAR
SMALL TANK WELDED
TO BASE OF LARGE TANK
SECTION
600
450
2250
2700
16 ga. GALV
SHEET METAL
OUTLET APRON
2700

FIGURE I TOBACCO CREEK EROSION PLOTS : CONSTRUCTION DETAILS

FIGURE 2 - LARGE TANK CALIBRATION
TOBACCO CREEK EROSION PROJECT

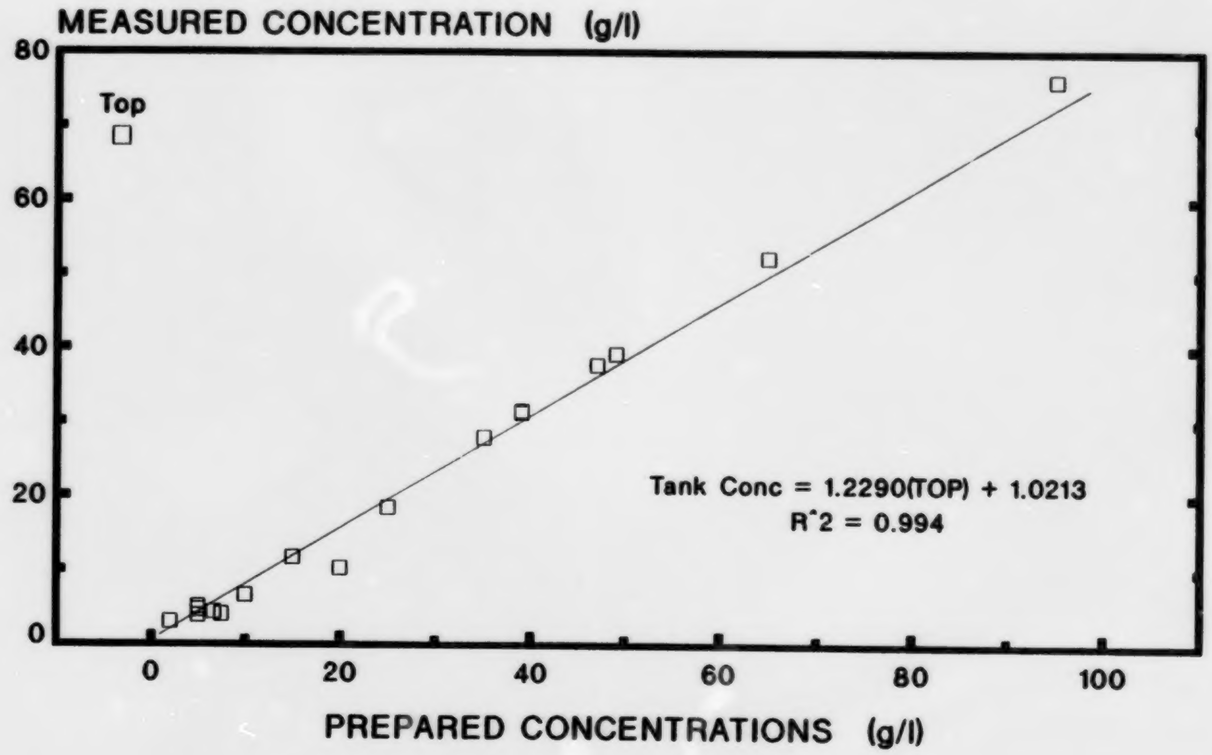
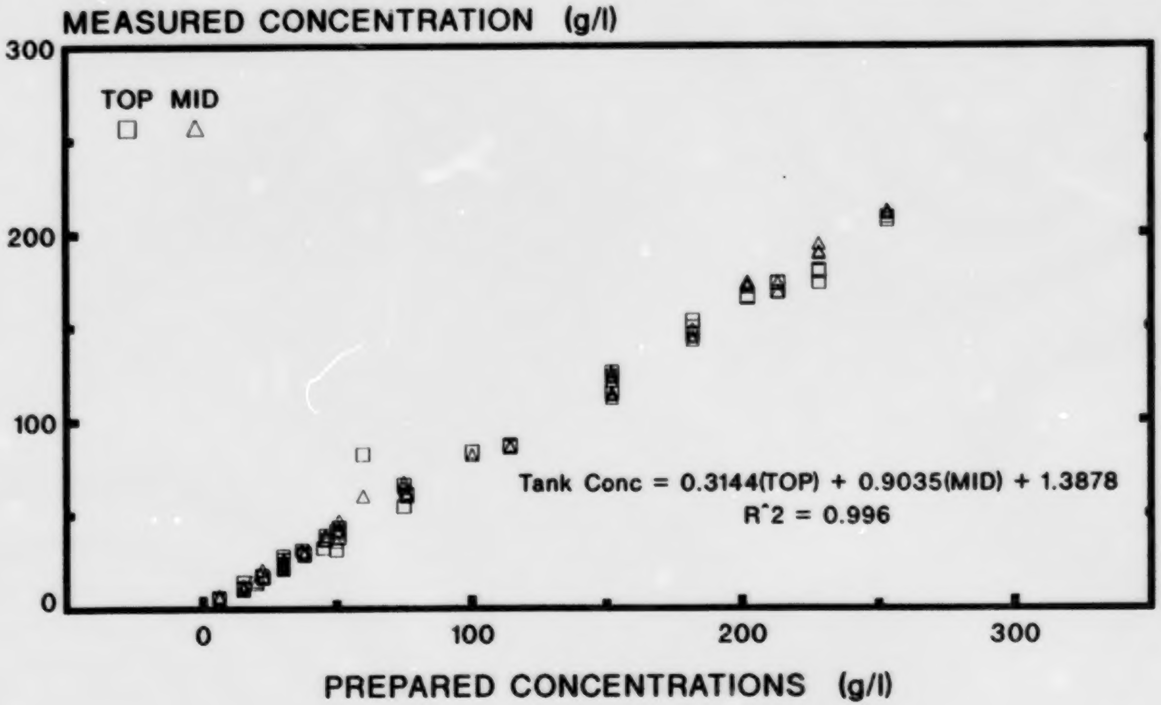


FIGURE 3 - SMALL TANK CALIBRATION
TOBACCO CREEK EROSION PROJECT



PFRA EROSION PLOTS, MIAMI: INTERIM RESULTS

J.M.W. Black[1], D.G. Smith[1] and W.J. Pauls[2]
[1]PFRA, Regina
[2]Department of Soil Science, University of Manitoba

ABSTRACT

The Universal Soil Loss Equation (USLE) is being used in Manitoba to select optimum soil conservation practices for land at risk to water erosion. Data from 16 water erosion plots located near Miami is being used to test the USLE. Results from 1986-88 (including snowmelt erosion) averaged 37.6 (+/- 6.2) t/ha from summerfallow plots compared to 37.1 t/ha estimated using the USLE. Measured losses for a wheat-wheat-canola rotation under conventional tillage and minimum tillage were 5.7 (+/- 4.0) and 7.7 (+/- 6.0) t/ha respectively compared to USLE estimated of 7.7 and 8.4 t/h. Snowmelt erosion on the summerfallow was 1.7% of total erosion during 1986-88. Snowmelt caused 5.7% and 8.8% of total water erosion on the wheat-wheat-canola rotation under conventional tillage and minimum tillage for the same period.

These early results suggest that the USLE may be quite successful in estimating sheet and rill erosion from summer precipitation in Manitoba. The measured contribution of snowmelt to total water erosion is low compared to other data reported for the Prairies.

INTRODUCTION

Sixteen water erosion plots were established near Miami, Manitoba during 1984-85 in order to test the Universal Soil Loss Equation (USLE) and to quantify variables for the equation. This paper discusses the results for 1986-88 in relation to expected erosion based on application of the USLE to Manitoba conditions.

MATERIALS AND METHODS

The plots are designed to capture all runoff and eroded soil from discrete areas on a hillside. The runoff is retained in collection tanks set into the ground. The suspension is mixed by a recirculating pump and sampled into glass jars. Samples are dried in an oven and the concentration of solution in the collection tank calculated. Details of plot design, operation and sampling methods are discussed in Black et al. (1990).

Rainstorm erosivity/intensity (EI) values for use in the USLE were calculated from recording raingage data collected at the plot site using the method detailed by Wischemier and Smith (1978). Storm EI values were summed to calculate the annual EI. EI values were also calculated from the data collected by Environment Canada at Deerwood, located three miles from the plots. Annual EI values for the Deerwood Station were fitted to the Wakeby distribution (Houghton, 1978) to calculate the return period of various annual EI values. A 22 year average of the annual EI values was used to evaluate the USLE R factor for Deerwood.

Soil erodibility (K) and crop cover (C) factors for the USLE were estimated using methods recommended by Wischemier and Smith (1978). The USLE slope steepness (S) factor was calculated for each plot after a topographical survey using the equation proposed by M^c^Cool et al. (1987):

$$S = 16.8 \sin B - 0.5$$

Where B is the angle of slope having a steepness of S expressed in percent.
The slope length (L) and erosion control practice (P) factors of the USLE were sent at unity by the experimental design.

The actual K factor for Gretna clay at the plot site was calculated from a re-arrangement of the USLE using data from the summerfallow plots:

$$K = \frac{A}{RLS}$$

Where: A = soil loss from plots due to rainfall
R = rainfall intensity
LS = USLE factors calculated from survey of plots

The USLE C factor for a particular rotation is the ratio of soil lost from cropped plots in a rotation to that lost from continuous summerfallow plots to rainfall (Wischemier and Smith, 1978). C factors were calculated for the wheat - wheat - canola conventional till and minimum till rotations.

RESULTS AND DISCUSSION

A total of 20 erosion events due to rain were sampled; 10, 7 and 3 in 1986, '87 and '88 respectively. All snowmelt erosion occurring in a particular year is considered to be a single event for the purposes of the experiment.

Rainfall Energy/Intensity

The annual EI values measured at the plot site for the three years were 1061.29, 1359.02 and 406.66 MJ mm/ha h y respectively. These relate to an average R factor of 832 MJ mm/ha h y for the Deerwood station between 1964 and 1987. An analysis of the Deerwood data suggests that an EI of 1200 MJ mm/ha h y can be expected every five years and that values of 1600 and 2000 MJ mm/ha h y can be expected within 10 and 20 year return periods. Consequently the EI values measured at the plots fall well within the expected range.

A plot of the Deerwood annual EI data (Figure 1) shows a striking periodicity of annual rainfall energy/intensity on a four year cycle since 1972. Since data from the plots is dependant on sampling the erosional effect of representative precipitation this periodicity can be used to determine the operational lifespan of the plots.

USLE K factor

Soil erodibility (K) factors calculated using data from the summerfallow plots are detailed in Table 1.

TABLE 1. ANNUAL K FACTORS (MEAN FOR PLOTS 1, 8, 11, 16)

Year	Mean K	Standard Error of the Mean*
1986	0.02449	+/-0.00396
1987	0.02247	+/-0.00433
1988	0.04184	+/-0.01374
Overall Mean	0.02960	+/-0.006148

* Implies that 2/3 of further samples would have a population mean within the specified range.

The mean K factor for the three years is very similar to the value of 0.0307 for the adjoining University plots reported by Wahome (1989). Wahome (1989) also calculated a K factor of 0.0273 for this soil using the methodology developed by Wischemier et al. (1971). These preliminary results suggest that the rainfall K factor for this soil is close to the expected value.

USLE C factor

The C factor for a particular rotation is the ratio of soil lost from cropped plots in a rotation to that lost from continuous summerfallow plots to rainfall. C factors for a rotation are usually more precise than for individual crops within a rotation. This is due to the fact that crop residues from a previous crop can affect erosion in a subsequent year.

Due to the large annual variability in precipitation and growing conditions a reliable estimate of C factors can only be established by collecting data over several cycles of a rotation.

The measured C factors for the conventional and minimum till wheat - wheat - canola rotations are detailed in Tables 2 and 3 below.

TABLE 2. C FACTORS FOR CONVENTIONAL TILL PLOTS

	Year	Mean C	Standard Error of the Mean
wheat	1986	0.508	+/-0.0439
canola	1987	0.027	+/-0.0027
wheat	1988	0.042	+/-0.0106
rotation average		0.193	+/-0.1579

TABLE 3. C FACTORS FOR MINIMUM TILL PLOTS

	Year	Mean C	Standard Error of the Mean
wheat	1986	0.347	+/-0.0442
canola	1987	0.027	+/-0.0036
wheat	1988	0.035	+/-0.0074
rotation average		0.137	+/-0.1827

As anticipated, the rotational C factors are larger for the conventional till plots than for the minimum till, thus indicating a potential for greater soil loss under conventional tillage.

Calculated C factors for these rotations using the methodology recommended by Wischemier and Smith (1978) are 0.227 and 0.206 for the conventional tillage and minimum till rotations respectively. These calculated factors are somewhat larger than those measured from the plots but are within the standard error of the means reported in Tables 2 and 3.

C factors used for these rotations used during conservation planning in North Dakota are 0.20 for conventional till and 0.13 for minimum till (USDA, SCS, 1988). These estimates are very similar to the results from the plots detailed above.

A large annual variability in the C factors for a particular crop within a rotation is to be expected due to differences in soil surface properties and vegetative cover between the summerfallow and cropped fields when an erosive rainfall occurs. An order of magnitude differences observed between the wheat crops of 1986 and 1988 for both rotations indicates that considerably more data is required in order to have confidence in rotational or crop specific C factors for the plots.

Soil Loss Data

A summation of the soil loss data for the plots is detailed in Table 4 below:

TABLE 4. MEAN ANNUAL SOIL LOSS DATA t/ha (including snowmelt)

	S/F		Minimum Till		Conventional Till	
SOIL LOSS						
1986	38.56	+/-7.02*	13.54	+/-1.73	19.64	+/-2.38
1987	46.44	+/-9.59	2.27	+/-0.18	2.19	+/-0.34
1988	25.08	+/-3.47	1.16	+/-0.18	1.29	+/-0.36
Mean	36.69	+/-6.24	5.66	+/-3.95	7.70	+/-5.97

* = Standard error of the mean

As anticipated, the order of soil loss was summerfallow > conventional till > minimum till for the three year means. An average loss of 36.7 t/ha on S/F represents a loss of approximately 3 mm of topsoil per year which is approximately 5 times larger than the rate of soil formation.

There is some variability between plots and between years due to soil surface conditions and due to climatic and rotational differences (Figure 2). Note that wheat was grown in 1985, 1986 and 1988 and that canola was grown in 1987 on all but the summerfallow plots.

The summerfallow plots displayed the greatest variability in erosion as evidenced by the large standard error of the means for individual years. This variability was dominantly a result of the larger erosion events. It is observed from Figure 2 that plot #1 (extreme left hand side) had higher soil loss than the other S/F plots in 1986 and 1987. Using LS factors to compensate for slight differences in slope between plots accounts for little of this variability. Different soil surface conditions or differences in soil erodibility are probable reasons. Further data is required in order to establish a definite trend.

The consistency of the data from the minimum till and conventional plots is apparent from an examination of Figure 2 and from the low standard error of the means for individual years reported in Table 4.

Snowmelt Erosion

The data to date indicate that snowmelt makes little contribution to the total soil loss (Table 5).

TABLE 5. AVERAGE SNOWMELT EROSION AS A PERCENTAGE OF TOTAL SOIL LOSS 1986-1988

Summerfallow	Minimum till	Conventional till
1.66%	8.83	5.71

The largest loss for a single melt event was 1.5 t/ha for plot #1 in 1987. In comparison the largest soil loss due to rainfall was 66.6 t/ha on plot #1, again in 1987. It is noted that this data represents three years which did not necessarily have the soil or climatic conditions for significant snowmelt erosion. Snowfall at the Deerwood station in the winters preceding the three sampling years was 175.6, 178.5 and 115.8 mm water equivalent respectively compared to a long term average of 183.7 mm.

Sheet and rill erosion due to snowmelt has been reported to constitute approximately 50% (range 19 -99%) of total water erosion from erosion plots in the Peace River area of Alberta (Van Vliet et al, 1984). Results form both sets of plots are short-term and are highly variable but suggest that sheet and rill erosion due to snowmelt are proportionally a smaller problem in Manitoba.

Comparison of plot results to estimates of erosion using the USLE

An estimate of potential soil loss for the three rotations was made using the USLE. A comparison between these calculated losses and the actual plot results is reported below:

TABLE 6. COMPARISON OF EROSION PLOT RESULTS WITH USLE CALCULATED SOIL LOSS (t/ha)

	USLE Estimate	Plot Result	USLE Estimate	Plot Result
	Including Snowmelt Erosion		Without Snowmelt Erosion	
Rotation				
Summerfallow	37.56	36.69	33.39	36.09
Conv. Till*	8.41	7.70	7.48	7.27
Min. Till	7.69	5.66	6.83	5.16

* Conventional Tillage
Minimum Tillage

Estimated erosion including snowmelt for the three rotations is slightly higher than the plot result but within 1 t/ha. The estimates for rainfall erosion are also slightly higher than the actual results (within 1.5 t/ha) for the wheat - wheat - canola rotations but 2.7 t/ha lower for the continuous summerfallow plots. These differences reflect the cumulative effect of discrepancies in individual plot measured factors compared to factors calculated using methodologies detailed by Wischemier and Smith (1978).

The USLE was developed using data from soils and climates quite different to those of the Canadian Prairies. Consequently the close similarity between the data from the plots and the USLE estimate detailed in Table 6 above is unexpected. This comparison, if confirmed by data from several cycles of the rotation, is very significant. It suggests that the USLE could give adequate precision for conservation planning in southern Manitoba.

CONCLUSIONS

Tentative conclusions which may be deduced from these early results are:

(1) That the USLE was quite successful in estimating erosion from a hillside in southern Manitoba in 1986-88.
(2) That both the USLE and the erosion plot results discriminated between minimum till and conventional till wheat - wheat - canola rotations.
(3) That the USLE may indeed have potential for the selection of conservation practices to control sheet and rill erosion in southern Manitoba.

Data from several more cycles of the rotation will be required in order to confirm these tentative conclusions.

REFERENCES

Black, J.M.W., Smith, D.G. and Pauls, W.J. 1990. Design and operation of the PFRA erosion plots at Miami, Manitoba. Proceedings of the 33rd Annual Manitoba Soil Science Society Meeting. Jan. 9-10, 1990. Winnipeg, Manitoba.

Houghton, J.C. 1978. Birth of a Parent: The Wakeby distribution for modeling flood flows. Water Resource. Res. 14(6): 1105-1109.

McCool, D.K., Brown, L.C., Foster, G.R., Mutchler, C.K. and Meyer, L.D. 1987. Revised slope steepness factor for the Universal Soil Loss Equation. Transactions of the ASAE 30(5): 1387-1396.

U.S.D.A., S.C.S. 1988. North Dakota Technical Guide. Soil Conservation Service. Bismark, N.D.

Van Vliet. L. J. P., Henning A. M. F. and Novak, M.D. 1986. Soil erosion loss monitoring and prediction under semi-arid agriculture in the Peace River Prairie Region of NW Canada in Land Evaluation for land-use planning and conservation in sloping areas. Publication #40. International Institute for Land Reclamation and Improvement. Wageningen, The Netherlands.

Wahome, E.K. 1989. Soil Erosion Measurements under Natural Rainfall for Evaluating the Universal Soil Loss Equation (USLE). Unpublished MSc thesis. The University of Manitoba. 208pp.

Wischemier, W.H. and Smith, D.D. 1978. Predicting rainfall erosion losses - a guide to conservation planning. USDA, Agriculture Handbook #537. 58pp.

Wischemier, W.H., Johnson, C.B. and Cross, B.V. 1971. A soil erodibility nomograph for farmland and construction sites. J. of Soil and Water Conservation. 26: 189-193.

FIGURE 1 - ANNUAL EI VALUES
DEERWOOD, MANITOBA

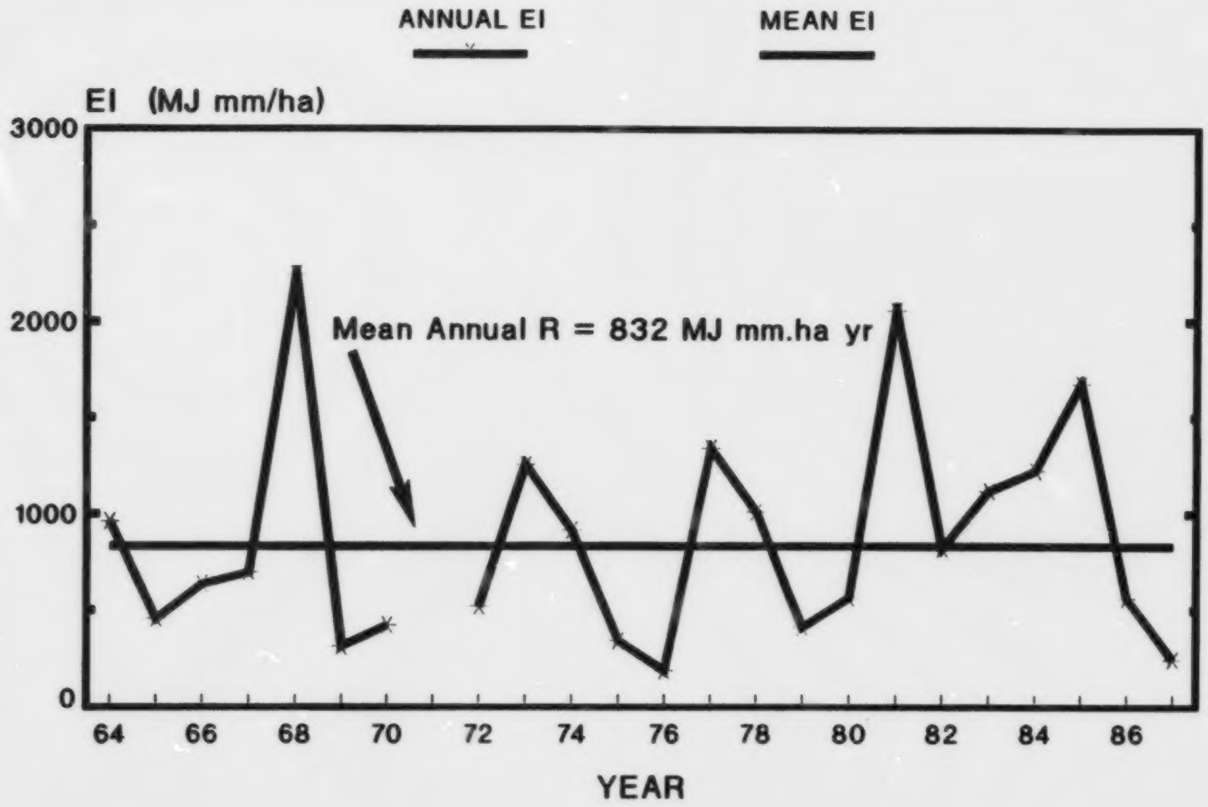
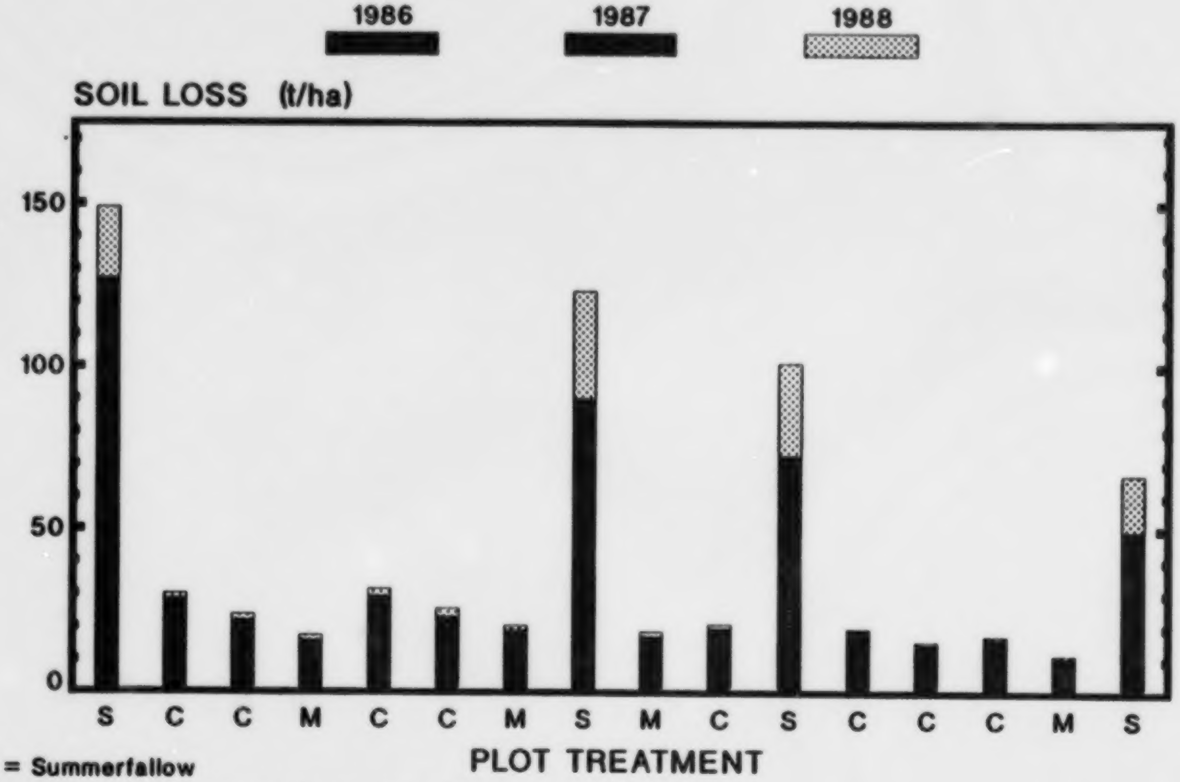


FIGURE 2 - PLOT SOIL LOSS 1986-1988
TOBACCO CREEK EROSION PLOTS



S = Summerfallow
C = wheat-wheat-canola, Conventioal tillage
M = wheat-wheat-canola, Minimum tillage

Comparison of Models for Describing Corn Yield Response to Nitrogen Fertilizer

M. E. Cerrato, University of Manitoba
A. M. Blackmer, Iowa State University

ABSTRACT

Decisions concerning optimum rates of fertilization directly or indirectly involve fitting some type of model to yield data collected when several rates of fertilizer are applied. Although several different models are commonly used to describe crop yield response to fertilizers, it is seldom explained why one model is selected over others. The objective of the work reported here was to compare and evaluate several models (linear-plus-plateau, quadratic-plus-plateau, quadratic, exponential, and square root) commonly used for describing the response of corn (Zea mays L.) to N fertilizer. The evaluation involved 12 site-years of data, each having 10 rates of N applied preplanting. All models fit the data equally well when evaluated by using the r^2 statistic. All models indicated similar maximum yields, but there were marked discrepancies among models when predicting economic optimum rates of fertilization. Mean (across all site-years) economic optimum rates of fertilization as indicated by the various models ranged from 128 to 379 kg N ha^{-1} at a common fertilizer-to-corn price ratio. Statistical analyses indicated that the most commonly used model, the quadratic model, did not give a valid description of the yield responses and tended to indicate optimal rates of fertilization that were too high. The quadratic-plus-plateau model best described the yields responses observed in this study. The results clearly show that, especially amid increasing concerns about the economic and environmental effects of overfertilization, the reason for selecting one model over others deserves more attention than it has received in the past.

INTRODUCTION

Selection of the most appropriate rate of nitrogen (N) fertilization is a major decision affecting the profitability of corn (Zea mays L.) production and the impact of agriculture on the environment. Directly or indirectly, decisions concerning optimal rates of fertilization involve fitting some type of model to yield data collected when several rates of fertilizer are applied. These decisions are more important now than ever before because N fertilizer use has increased greatly over the past three decades and because there is increasing concern about environmental impacts associated with the use of this fertilizer.

Several different response models have been used to identify economic optimum rates of N fertilization, and many researchers have noted that these models often disagree when identifying these rates (Abraham and Rao, 1965; Anderson and Nelson, 1971, 1975; Barreto and Westerman, 1987; Nelson et al., 1985; Blackmer and Meisinger, 1988). However, a standardized procedure for selecting one model over others has not been adopted. Moreover, the importance of the disagreements among models when identifying economic optimum rates of fertilization has received little attention in recent discussions evaluating trade-offs between the profitability and the environmental costs of crop production. And decisions concerning optimal rates of fertilization usually are based on the use of a model with little or no discussion of why this model was selected over other models.

The objective of this study was to compare and evaluate models commonly used for identification of economic optimum rates of fertilization. The study involved fitting each model to results of yield trials having 10 rates of N and comparing (i) predicted economic optimum rates of fertilization, (ii) predicted maximum yields, (iii) coefficients of determination, (iv) trends in differences between observed data and predicted data, and (v) potential economic losses associated with making incorrect decisions when selecting a response model. The results clearly indicate that model selection is a major factor affecting what rates are identified as being optimal and, therefore, that the reason for selecting one model over others deserves more attention than it has received in the past.

MATERIALS AND METHODS

Field plots were established at four locations in 1985 and at two locations in 1986 as indicated in Table 1. All plots were established in nonirrigated fields under production agriculture and, except for N application and grain harvest, were managed in accordance with the farmers' normal practices. All sites had been planted to corn the year before the plots were established. Nitrogen treatments were ammonium sulfate broadcast and incorporated into the soil at ten rates (0, 28, 56, 84, 112, 140, 168, 224, 280, and 336 kg N ha^{-1}) shortly before planting. After the plots were established, the annual N treatments applied to each plot were not changed. The plots were 12.2 by 4.6 m (six 76-cm rows) or 12.2 by 3.9 m (four 97-cm rows) and were arranged in a randomized complete-block design with three replications. Plant density ranged from 50,000 to 70,000. Grain yields were measured by hand-harvesting 7.5-m segments of the two center rows and were adjusted to 15.5% moisture content.

Five response models (linear-plus-plateau, quadratic-plus-plateau, quadratic, exponential, and square root) were fit to the data from each site-year by using the NLIN (Ihnen and Goodnight, 1985) or GLM (Spector et al., 1985) procedure.

The linear-plus-plateau model is defined by equations 1 and 2,

$$Y = a + bX \quad \text{if } X<C \qquad [1]$$

$$Y = P \quad \text{if } X>C \qquad [2]$$

where Y is the yield of grain (Mg ha^{-1}) and X is the rate of N application (kg ha^{-1}); a (intercept), b (linear coefficient), C (critical rate of fertilization, which occurs at the intersection of the linear-response and the plateau lines), and P (plateau yield) are constants obtained by fitting the model to the data.

The quadratic-plus-plateau model is defined by equations 3 and 4,

$$Y = a + bX + cX^2 \quad \text{if } X<C \qquad [3]$$

$$Y = P \quad \text{if } X>C \qquad [4]$$

where Y is the yield of grain (Mg ha^{-1}) and X is the rate of N application (kg ha^{-1}); a (intercept), b (linear coefficient), c (quadratic coefficient), C (critical rate

Table 1. Information describing the experimental sites.

		Soil		
Site	Location	Series	Subgroup	Years studied
1	Marengo	Nevin	Aquic Argiudoll	1985,1986,1987
2	Williamsburg	Mahaska	Aquic Argiudoll	1985
3	Kalona	Bremer	Typic Haplaquoll	1985,1986,1987
4	Iowa City	Mahaska	Aquic Argiudoll	1985
5	Ames 1	Nicollet	Aquic Hapludoll	1985,1986,1987
6	Ames 2	Canisteo	Typic Haplaquoll	1985,1986,1987
7	Ida Grove	Marshall	Typic Hapludoll	1986,1987
8	Holstein	Galva	Typic Hapludoll	1986,1987

of fertilization, which occurs at the intersection of the quadratic response and the plateau lines), and P (plateau yield) are constants obtained by fitting the model to the data.

The quadratic model is defined by equation 5,

$$Y = a + bX + cX^2 \qquad [5]$$

where Y is the yield of grain (Mg ha^{-1}) and X is the rate of N application (kg ha^{-1}); a (intercept), b (linear coefficient), c (quadratic coefficient) are constants obtained by fitting the model to the data.

The exponential model (i.e., the Mitscherlich model) is defined by equation 6,

$$Y = M(1\text{-}EXP^{-c(X+b)}) \qquad [6]$$

where Y is the yield of grain (Mg ha^{-1}) and X is the rate of N application (kg ha^{-1}); M (the maximum yield attainable), c, and b are constants obtained by fitting the model to the data. The c constant corresponds to the Mitscherlich effect factor (see National Academy of Sciences, 1961), and the b constant estimates the amount of soil-derived available N.

The square root model is defined by equation 7,

$$Y = a + bX + cX^{1/2} \qquad [7]$$

where Y is the yield of grain (Mg ha^{-1}) and X is the rate of N application (kg ha^{-1}); a (intercept), b (linear coefficient), c (square root coefficient) are constants obtained by fitting the model to the data.

Coefficients of determination (r^2 values) for models were determined by use of regression analyses. For the quadratic and square root models, predicted maximum yields were obtained by equating the first derivatives of the response equations to zero, solving for X, substituting the values of X into the response equations, and solving for Y. For the exponential model, which predicts that maximum yields are achieved only when fertilizer applications are at infinity, predicted maximum yields were considered to be 99.9% of M (Barreto and Westerman, 1987). For the linear-plus-plateau and quadratic-plus-plateau models, the plateau yields were considered to be maximum yields. Except for the linear-plus-plateau model, predicted economic optimum rates of fertilization were calculated by equating the first derivatives of the response equations to a selected fertilizer-to-corn price ratio and solving for X (Heady et al., 1955; National Academy of Sciences, 1961; Nelson et al., 1985). For the linear-plus-plateau model, economic optimum rates of fertilization were identified by locating the intersection of the two lines (Waugh et al., 1973; Ihnen and Goodnight, 1985).

RESULTS AND DISCUSSION

Response data for corn in 1985 are not included in this study because statistically significant responses to N treatments were not observed. The lack of response probably was caused by carry-over of N from 1984. Such responses are not representative of those expected during sustained corn production at the treatments applied.

Data in Table 2 show considerable disagreement among the models when they are used to identify economic optimum rates of fertilization at a given fertilizer-to-corn price ratio. Some models were quite consistent in indicating higher optimal rates than others. The magnitude of these differences indicates a need to justify selection of one model over other models when discussing economic and environmental trade-offs associated with N fertilization.

Data in Table 3 indicate that, when evaluated by using the R^2 statistic, the five models seem to fit the yield data about equally well. Because there is little biological basis for selecting one model over others (Mead and Pike, 1975; Nelson et al., 1985), the r^2 statistic usually is used to justify the use of a particular model. The limitation of using the r^2 statistic to select a model is further illustrated in Fig. 1, which shows how each of the models fits the data from site 5 in 1986. Because there is only one correct economic optimum rate of fertilization for each site-year, the observation that models having similar r^2 values differ greatly in determined values of economic optimum rates indicates that r^2 value is not a reliable criterion for selection of a model for identification of economic optimum rates of N fertilization.

The numbers in parentheses in Table 3 illustrate that use of the r^2 statistic can result in a false sense of confidence concerning the ability of models to describe responses to N when too few treatments are used. That is, greater r^2 values were obtained when only four N treatments were considered than when all ten treatments were considered. Although these differences can be reduced by adjusting the r^2 values for degrees of freedom (Darlington, 1968; Judge et al., 1982; Blackmer and Meisinger, 1988), this adjustment usually has not been made in fertilizer response studies. We believe this is a notable problem because most fertilizer N response studies involve four or fewer N

Table 2. Economic optimum rates of N fertilization predicted by each model at each site-year.†

	Predicted economic optimum rates of fertilization				
Site-year	Linear plus plateau	Quadratic plus plateau	Quadratic	Exponential	Square root
	kg ha^{-1}				
1-86	120	173	227	242	344
2-86	198	302	302	493	323
3-86	130	196	227	218	276
4-86	130	195	236	294	504
5-86	104	163	222	222	287
6-86	133	212	241	300	680
1-87	94	124	188	156	153
2-87	111	108	141	87	75
3-87	102	153	211	194	221
4-87	152	215	245	317	870
5-87	115	154	215	205	258
6-87	149	216	241	292	560
Mean	128	184	225	252	379

† The fertilizer-to-corn price ratio used was 3.36, which is consistent with values of \$ 0.0987 kg^{-1} (\$ 2.50 bu^{-1}) for corn and \$ 0.33 kg^{-1} (\$ 0.15 lb^{-1}) for fertilizer.

treatments and because the ability of models having high r^2 values (e.g., 0.90 or higher) to identify optimum rates of fertilization has not been questioned.

Data in Table 4 show that the models predicted similar maximum yields at each site-year, although the square root model tended to predict slightly higher maximum yields than did the other models. The validity of this model for predicting maximum yields, however, is questionable because seemingly absurd rates of fertilization were indicated as necessary to achieve maximum yields. These rates were at least 1.3 times higher than those indicated by any other model, and they averaged 709 kg ha^{-1}. Other than this consideration, the predicted maximum yields provide little basis for selection of one model over others.

Table 3. Coefficients of determination (R^2 values) for models describing relationships between N rate and grain yields.[†]

	R^2 values				
Site-year	Linear plus plateau	Quadratic plus plateau	Quadratic	Exponential	Square root
1-86	0.90 (0.93)	0.91 (0.93)	0.89 (0.93)	0.91 (0.93)	0.87 (0.93)
2-86	0.96 (0.98)	0.95 (0.98)	0.97 (0.98)	0.94 (0.97)	0.90 (0.97)
3-86	0.78 (0.96)	0.82 (0.96)	0.82 (0.97)	0.84 (0.94)	0.84 (0.93)
4-86	0.92 (0.99)	0.91 (0.99)	0.90 (0.97)	0.89 (0.99)	0.83 (0.99)
5-86	0.94 (0.95)	0.95 (0.96)	0.92 (O.95)	0.95 (0.96)	0.92 (0.96)
6-86	0.94 (0.98)	0.95 (0.98)	0.95 (0.97)	0.94 (0.98)	0.91 (0.98)
1-87	0.85 (0.80)	0.85 (0.80)	0.79 (0.82)	0.76 [‡]	0.73 (0.89)
2-87	0.24 (0.77)	0.23 (0.77)	0.22 (0.78)	0.22 [‡]	0.22 (0.81)
3-87	0.73 (0.82)	0.75 (0.83)	0.75 (0.80)	0.75 (0.83)	0.74 (0.83)
4-87	0.93 (0.91)	0.92 (0.94)	0.91 (0.92)	0.90 (0.94)	0.84 (0.94)
5-87	0.89 (0.94)	0.88 (0.93)	0.86 (0.90)	0.87 (0.94)	0.84 (0.90)
6-87	0.91 (0.95)	0.92 (0.97)	0.91 (0.96)	0.91 (0.97)	0.89 (0.97)
Mean	0.83 (0.92)	0.84 (0.92)	0.82 (0.91)	0.82 (0.95)	0.79 (0.93)

[†] Values in parentheses indicate R^2 values obtained when models were fitted to response data from only 4 rates of N (0, 112, 224, 336 kg ha^{-1}).

[‡] Values could not be obtained because the model failed to fit yield data from these sites.

Data presented in Table 5 show that significant discrepancies among models in indicated economic optimum rates occurred over a wide range of fertilizer-to-corn price ratios. These discrepancies became larger as the price of fertilizer decreased relative to the price of corn. This should be expected because, with all models except the linear-plus-plateau model, lower fertilizer prices shift optimal rates of fertilization onto flatter portions of the response curves, where small differences in slope correspond to relatively large differences in rates of fertilization. With the linear-plus-plateau model at reasonable price ratios, the economic optimum rate of fertilization is independent of the price ratio (Waugh et al., 1973). The price ratio used in Table 2 is representative of price ratios common during the past decade.

Figures 2a through 2e show analyses of the deviations from regression,

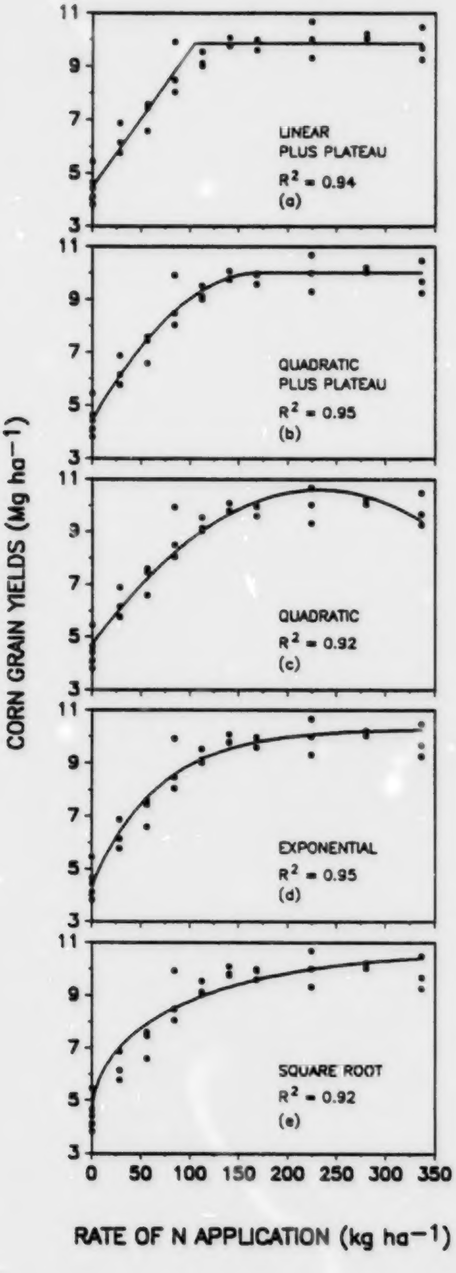


Figure 1. Example of how each of the five models fits the response data for one site-year (site 5 in 1986).

Table 4. Maximum yields predicted by each model at each site-year.

	Predicted maximum yields				
Site-year	Linear plus plateau	Quadratic plus plateau	Quadratic	Exponential	Square root
	Mg ha^{-1}				
1-86	11.0	11.1	11.7	11.4	11.9
2-86	12.9	13.2	13.2	15.0	10.5
3-86	10.7	11.0	11.3	11.1	11.2
4-86	11.1	11.3	11.9	11.9	13.3
5-86	9.9	9.9	10.6	10.2	10.5
6-86	8.2	8.4	8.8	9.0	12.6
1-87	8.6	8.5	9.2	8.6	8.5
2-87	8.5	8.4	8.6	8.4	8.4
3-87	9.7	9.8	10.4	9.9	9.9
4-87	10.2	10.3	10.7	11.0	15.7
5-87	9.3	9.3	9.8	9.8	9.7
6-87	9.9	10.0	10.4	10.5	12.4
Mean	10.0	10.1	10.6	10.6	11.2

Table 5. Mean (over 12 site-years) predicted economic optimum rates of fertilization at various fertilizer-to-corn price ratios.

	Mean predicted economic optimum rates				
Price-ratio	Linear plus plateau	Quadratic plus plateau	Quadratic	Exponential	Square root
	kg ha^{-1}				
2	128	190	233	296	490
4	128	182	221	237	347
6	128	174	208	203	261
8	128	165	196	179	205
10	128	157	184	160	163

or residuals (i.e., yields observed minus yields predicted by the model), for each model. In these figures, points above the horizontal line indicate that the model underpredicted yields and points under this line indicate that the model overpredicted yields. These figures show that some models fit the response data with less systematic bias than others and suggest that the exponential and the square root models fit least well. A statistical test (the Kolmogorov test; Delong, 1985) indicated that the residuals obtained from the quadratic and square root models do not have a standard normal distribution (D values of 0.096 and 0.081, $P < 0.05$) and, therefore, that these models do not give a valid description of the yield response data.

The bias of each model when determining economic optimum rates of fertilization is easier to interpret in Fig. 3a through 3e. In these figures, the data points for each site-year are positioned relative to predicted economic optimum rates of fertilization, which are located in the centers of the figures. Figure 3c shows that the quadratic model tended to overestimate yields at the rates of fertilization it identified as optimum. Because of the sharpness of the quadratic response curve near economic optimum and maximum, this model often identified unattainable yields as being optimum. This figure also shows a tendency for the quadratic model to over-estimate the slope of the response curve at rates of fertilization slightly less than economic optimum. The existence of this trend was confirmed by a linear correlation analysis, which revealed a significant ($r = -0.40$, $P < 0.01$) slope for the points between -175 and +10 kg N ha^{-1} in Fig. 3c. This trend is very important because the economic optimum rate of fertilization is calculated by using the slope of the response curve. These observations indicate that the quadratic model had a tendency to indicate economic optimum rates of fertilization that were too high.

Although the trend is more difficult to quantify, it seems that the linear-plus-plateau model has a tendency to overestimate yields in the portion of the response curve close to where economic optimum rates of fertilization are indicated (i.e., on the vertical line in the center of the figure). This tendency is evidenced by a mean value of -0.240 Mg ha^{-1} for the 22 points between ±25 kg ha^{-1} in Fig 3a. This overestimation is consistent with the nature of this model, which has an abrupt discontinuity at the point identified as economic optimum. Such abrupt discontinuities are difficult to accept from a biological point of view. The overestimation of yields at this discontinuity, of course, results in identification of economic optimum rates of fertilization that are too low.

It can be concluded from Fig. 2 and 3 that the quadratic-plus-plateau model best describes the yield responses observed in this study. Figure 2 and the accompanying discussion indicate that the square root, quadratic, and exponential models do not fit the data as well as the quadratic-plus-plateau and the linear-plus-plateau models. Figure 3 and the accompanying discussion indicate that the linear-plus-plateau and the quadratic models do not fit the data as well as the quadratic-plus-plateau model. These figures illustrate the importance of having many rates of fertilizer at many site-years when trying to

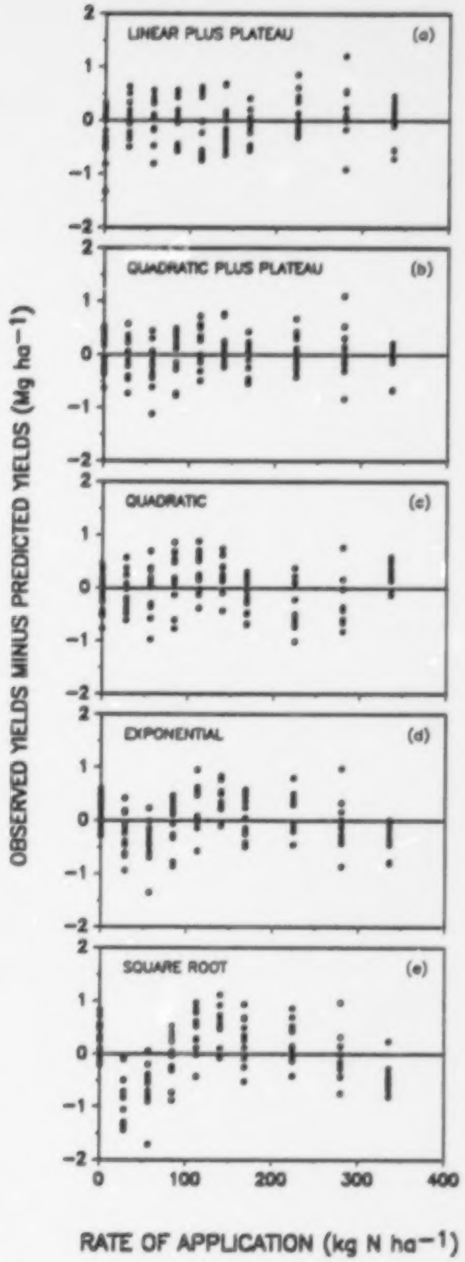


Figure 2. Deviations from regressions (observed yields minus predicted yields) observed when all models were fit to individual site-years. Each point represents a treatment mean for a site-year.

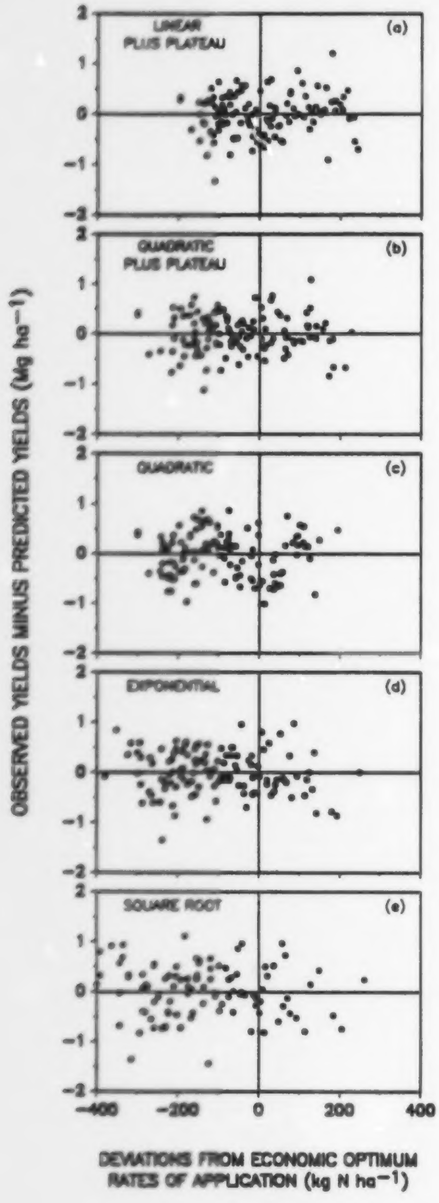


Figure 3. Deviations from regressions observed when all models were fit to individual site-years. Points from each site-year are positioned relative to predicted economic optimum rates of fertilization (at a fertilizer-to-corn price ratio of 3.36), which are located in the centers of the figures.

select the most appropriate model to identify economic optimum rates of fertilization. The importance of having many rates also applies when evaluating the cost effectiveness of treatments that conserve fertilizer N (Blackmer, 1986).

Table 6 shows the mean losses of income resulting from incorrect decisions concerning fertilization rates for all possible combinations of incorrect decisions involving the models studied. All losses shown in the upper-right half of Table 6 occur because less-than-optimal yields were attained. For example, \$47 ha^{-1} would be lost because of low yields if the quadratic-plus-plateau model were correct but the linear-plus-plateau model was used to identify optimum rates of fertilization. All losses in the lower-left half of the table occur because fertilizer was added without attaining an increase in yield. The large mean loss calculated when the quadratic model is assumed to be correct and the square root model is used to identify economic optimum rates of fertilization is, of course, absurd. It occurred because the square root model usually predicts higher optimal rates than does the quadratic and because the quadratic model predicts rapid decreases in yields when fertilizer is applied at higher-than-optimal rates.

The information presented in Table 6 is important because it challenges the common notion among growers that it is more profitable to apply too much fertilizer rather than too little fertilizer. Growers influenced by this notion would select the quadratic model over the quadratic plus-plateau model amid uncertainty concerning which model is correct. The analyses in Table 6 indicate this decision would be unwise for economic as well as for environmental reasons. If it were assumed that the response data analyzed are representative of responses of corn to N in Iowa and that the quadratic-plus-plateau model accurately describes this response, then it would be concluded from Table 6 that farmers are losing \$16 ha^{-1} if they are applying fertilizer in accordance with the quadratic model (at the price ratios used in this table). The extra 41 kg N ha^{-1} of fertilizer would result in the consumption of the equivalent of 84 liters ha^{-1} of diesel fuel (Lucas et al., 1977) used during the manufacture and transport of the fertilizer. If it were assumed that the mean annual percolation of water through soils used for corn production in Iowa is 10 cm (Stewart et al., 1975) and that all the extra N is leached with this water, then the extra fertilizer would result in a mean increase of 41 mg N kg^{-1} in the water percolating from the corn fields. The environmental importance of this extra N on groundwater quality can be evaluated by comparison with the current public health limit of 10 mg N kg^{-1} for nitrate in drinking water. These observations illustrate the potential economic and environmental importance of selecting the best response model when making fertilizer N recommendations for major crops like corn, which covers 5 X 10^6 ha in Iowa alone.

With regard to the assumption that the response data analyzed are representative of responses of corn to N in Iowa, it is relevant that the mean economic optimum rate of fertilization predicted by the quadratic model for the site-years included in this study (i.e., 225 kg N ha^{-1}) corresponds almost exactly with the 226 kg N ha^{-1} that would be recommended by using Iowa

Table 6. Mean (over 12 site-years) economic losses of income resulting from incorrect selection of response model.

Model used to identify optimum rate	Mean economic losses[†]				
	If linear plus plateau is correct	If quadratic plus plateau is correct	If quadratic is correct	If exponential is correct	If square root is correct
	----------	----------	$\$$ ha^{-1}	----------	----------
Linear plus plateau	0	47	92	59	105
Quadratic plus plateau	19	0	19	14	56
Quadratic	32	16	0	7	42
Exponential	43	25	33	0	11
Square root	86	68	664	35	0

[†] Calculations are based on a fertilizer-to-corn price ratio of 3.36.

State University guidelines (Voss, 1982) to achieve the optimum yields observed in this study (as indicated by the quadratic model). This is relevant because corn responses to N usually have been described by using the quadratic model.

CONCLUSIONS

The results of this study clearly indicate that the reason for selecting one model over others deserves more attention than it has received in the past when making decisions concerning amounts of fertilizer required for profitable crop production. These decisions could relate to selection of the most profitable rate of fertilization on a field scale or to weighing the costs (environmental as well as economic) and benefits of N fertilization on a regional or national scale. The quadratic-plus-plateau model best described the yield responses observed in this study.

This work was supported in part from the Fertilizer Trust Account of the Iowa Department of Agriculture and Land Stewardship and in part by the Integrated Farm Management Demonstration Program of The Agricultural Energy Management Fund, State of Iowa, through the Iowa Department of Agriculture and Land Stewardship.

LITERATURE CITED

Abraham, T. P., and V. Y. Rao. 1965. An investigation on functional models for fertilizer response studies. J. Indian Soc. Agric. Stat., 18:45-61.

Anderson, R. L., and L. A. Nelson. 1971. Some problems in estimation of single nutrient functions. Bull. Int. Stat. Inst. 44:203-222.

Anderson, R. L., and L. A. Nelson. 1975. A family of models involving intersecting straight lines and concomitant experimental designs useful in evaluating response to fertilizer nutrients. Biometrics 31:303-318.

Barreto, H. J., and R. L. Westerman. 1987. YIELDFIT: A computer program for determining economic fertilization rates. J. Agron. Educ. 16:11-14.

Blackmer, A. M. 1986. Potential yield response of corn to treatments that conserve fertilizer nitrogen in soils. Agron J. 78:571-575.

Blackmer, A. M. and J. J. Meisinger. 1989. Re-examination of the methodology used for selecting nitrogen inputs into crop production. J. Contam. Hydrol. (In press).

Darlington, R. B. 1968. Multiple regression in psychological research and practice. Psychol. Bull. 69:161-182.

Delong, D. M. 1985. The univariate Procedure. p. 1181-1191. In SAS User's Guide: Basics, 1985 ed. SAS Institute Inc., Cary, NC.

Heady, E. O., Pesek, J. T., and Brown, W.G. 1955. Crop response surfaces and economic optima in fertilizer use. Iowa Exp. Stn. Res. Bull. 424.

Ihnen, L. A., and J. H. Goodnight. 1985. The NLIN procedure. p. 575-606. In SAS User's Guide: Statistics, 1985 ed. SAS Institute Inc., Cary, NC.

Judge, G. G., R. C. Hill, W. E. Griffiths, H. Lütkepohl, and T. Lee. 1982. Introduction to the theory and practice of econometrics. John Wiley and sons Inc. New York, NY.

Lucas, R. E., J. B. Holtman, L. J., and Connor, L. J. 1977. Soil carbon dynamics and cropping practices. p. 333-351. In W. Lockeretz (ed.) Agriculture and Energy. Academic Press Inc., New York, NY.

Mead, R., and D. J. Pike. 1975. A review of response surface methodology from a biometric viewpoint. Biometrics 31:803-851.

National Academy of Sciences-National Research Council, Committee on Economics of Fertilizer Use of the Agricultural Board, 1961. Statistical methods of research in economic and agronomic aspects of fertilizer response and use. NAS-NRC Pub. 918, National Academy of Sciences-National Research Council, Washington, D.C.

Nelson, L. A., R. D. Voss, and J. T. Pesek. 1985. Agronomic and statistical evaluation of fertilizer response. p. 53-90. In O. P. Engelstad (ed.), Fertilizer Technology and Use, 3rd ed., American Society of Agronomy, Madison.

Spector, P. C., J. H. Goodnight, J. P. Sall, and W. S. Sarle. 1985. The GLM procedure. p. 433-506. In SAS User's Guide: Statistics, 1985 ed. SAS Institute Inc., Cary, NC.

Stewart, B. A., D. A. Woolhiser, W. H. Wischmeier, J. H. Caro, and M. H. Frere. 1975. Control of water pollution from cropland. Vol 1 USDA Rep. ARS-H-5-1. U.S. Government Printing Office, Washington, DC.

Voss, R. D. 1982. General guide for fertilizer recommendations in Iowa. Iowa Agric. Home Econ. Exp. Stn., Iowa Coop. Ext. Serv. (Publ.) Ag-65.

Waugh, D. L., R. B. Cate, and L. A. Nelson. 1973. Discontinuous models for rapid correlation, interpretation, and utilization of soil analysis and fertilizer response data. Technical Bulletin 7. International Soil Fertility Evaluation and Improvement Program. North Carolina State University. Raleigh, NC.

An Expert System for Fertilizer Selection

M. Evans, C. Li, P. Duddridge, M. Wilgosh, R. Mondor
Department of Computer Science
University of Manitoba
Winnipeg, Manitoba
R3T 2N2

and

D. Flaten
Faculty of Agriculture
University of Manitoba
Winnipeg, Manitoba
R3T 2N2

ABSTRACT

Artificial Intelligence (AI) methodologies have demonstrated the ability to provide more advanced forms of decision support by automating the expert decision making process. Systems developed using these methodologies are commonly known as expert systems since they are programmed with knowledge and skill extracted from human experts. We have recently applied expert systems technology to develop a demonstration prototype of a fertilizer selection advisor (FSA). The program represents an integration of conventional computing and expert systems technology designed to provide expert recommendations enabling farmers to obtain the best return on their fertilizer investment. We have found this application to be well-suited to expert systems technology as the problem relies heavily on knowledge describing the relevant factors involved in selecting fertilizers. In addition, the incremental development methodologies used to create expert systems allowed us to gradually expand the scope of the system's knowledge and thus control the complexity surrounding the decision making involved in generating fertilizer recommendations. We were able to program the system with sufficient knowledge enabling it to focus its attention towards relevant information only, thus reducing the problem space to a manageable size and significantly improving the efficiency of the system. Another key benefit of expert systems, the ability to explain the decision making process, was also incorporated into the FSA prototype. This facility enables the users to query the system about the decision making process, thus providing the users with a better understanding of the underlying assumptions, facts, and reasoning used to generate recommendations. The FSA prototype, therefore, demonstrates the feasibility of employing expert systems technology in conjunction with conventional computing techniques to extend the level of decision support that can be provided in agricultural applications.

1 INTRODUCTION

Recently, a number of research and industrial organizations have been exploring the use of artificial intelligence (AI) techniques to tackle problems that have been difficult to solve using conventional computing technology [McNurlin, 1988], [Miller, 1986]. Systems developed using these techniques offer many significant new capabilities because they explicitly represent and reason with knowledge supplied by human experts[1] [Waterman, 1986], [Harmon, 1985]. In particular, AI offers an opportunity to (1) capture, retain, and replicate expertise that has accrued over many years of experience, (2) extend the level of computerized decision support by providing users with the ability to request and receive explanations of the knowledge and reasoning used to make decisions, and (3) address difficult problems using incremental development techniques which control problem complexity by allowing a solution to gradually evolve over time [Luger et al., 1989].

This paper describes an expert system prototype of a fertilizer selection advisor (FSA) designed to provide expert recommendations enabling farmers to obtain the best return on their fertilizer investment. To build the system, we employed a development strategy, commonly used in the construction of expert systems, which consists of (1) defining the problem including the scope of decisions to be addressed, the factors involved in making decisions, and the role of the expert system, (2) conceptualizing a model that defines the knowledge and reasoning involved in making decisions, (3) formulating the knowledge representation and reasoning facilities required to implement the conceptual model, (4) implementing the conceptual model using an appropriate development tool which provides the facilities outlined in 3, and (5) testing the ensuing implementation to identify strengths and weaknesses that will lead to progressive revisions and extensions to the problem definition, the conceptual model, the problem formulation, and/or the implementation of the model [Buchanan et al., 1983]. The following sections describe the results of our initial work and the current implementation of the prototype system.

2 PROBLEM DEFINITION

At present, Manitoba Agriculture has a system in place for aiding Manitoba farmers and advisors in making decisions concerning fertilizers. The main component of this system is the Provincial Soil Testing Laboratory. Farmers, agricultural representatives, and fertilizer dealers send soil samples to the Provincial Lab for analysis of nutrient concentrations in the soil. On the basis of this analysis, fertilizer recommendations are provided. For all crops, a standard soil test recommendation is given which suggests a *single application rate* for each nutrient required. These recommendations are said to provide a good economic return under reasonable Manitoba growing conditions.

---

[1] These systems are commonly referred to as expert systems or knowledge-based systems. We will use the terms interchangeably.

This system has been criticized by many as being somewhat crude. For instance, each farmer deals with a different set of crop and fertilizer prices and a unique set of growing conditions. One farmer, for example, may be able to capitalize on low prices for anhydrous ammonia whereas, a neighbor may not because of a lack of suitable equipment. Growing conditions, being highly dependent on soil type and climatic factors, are also highly variable across many areas of the province as well as from year to year. Therefore, for the best results, farmers should have the data from the soil test interpreted by an agronomist and tailored towards their specific conditions before fertilization begins.

Ideally, recommendations concerning additional crop nutrients should take into consideration the following variables:

- soil type;
- concentration of nutrients already in the soil (*i.e.*, soil test results);
- soil moisture content at planting time;
- regional climatic conditions including growing season precipitation;
- the effect of method, cost, and time of application on toxicity constraints and the efficiency of added nutrients;
- fertilizer compound nutrient analysis, form, and price;
- the client's own preferences; a farmer may have certain equipment constraints, dollar constraints, safety preferences, or simply a desire to stick with tradition.

Each of the above variables can take on many values. For example, climatic conditions, soil type, and soil moisture content may take on a variety of different values from one field to another and from one year to another. Fertilizers can be applied either in the spring or fall using a single or combination of the following methods: banded prior to planting, banded with the seed, banded beside/under the seed, or broadcast. The common nutrients, being nitrogen, phosphate, potash, and sulphur, can be combined in numerous ways to yield the various fertilizer compounds in dry, gas, or liquid form. In addition, preferences of the user should be addressed in order to provide a customized fertilizer recommendation. These preferences may include: equipment constraints, financial constraints, risk aversion, and farming traditions. The difficulty in making effective fertilizer recommendations is in considering how to work with all the variables to arrive at the best recommendation—we call this the fertilizer problem.

In theory, to solve the fertilizer problem, one could consider all potential recommendations by generating all possible combinations of the variables and selecting the most cost effective alternatives (*i.e.*, an exhaustive search of the problem space). In fact, such an approach is not viable since the computational complexity of this problem is exponential in nature, implying that a brute force search of the problem space may take a very long time. After consultation with various experts in crop management and soil sciences, we determined that agronomists do not use a formal algorithm for generating solutions to the fertilizer problem. Instead, agronomists rely on experience, intuition, and heuristics when making fertilizer decisions. The lack of a formal algorithm, combined with the recognition of the heuristic methods, suggested that the fertilizer problem was a good candidate for expert systems technology.

3 CONCEPTUALIZATION

The main objective in formulating a recommendation for fertilizer application is to maximize dollar returns on fertilizer investment. Returns are calculated by subtracting the total production costs (*e.g.*, fertilization costs, cultivation costs, pesticide costs, *etc.*) from the gross revenue procured from the sale of the harvested produce. Consider first the effects of a single nutrient, nitrogen. If it is determined that the supply of nitrogen in the soil prior to fertilization is not sufficient to yield an optimal return,[1] the cost of adding more nitrogen to the soil is considered. The total cost of additional nitrogen is equal to the sum of the cost of the fertilizer itself (*i.e.*, the cost per unit increment of nitrogen times the number of increments) plus the application cost. Application costs are dependent on the method of application and include such expenditures as fuel, repair, and labour. The cost per unit increment of nitrogen supply is a function of fertilizer compound price, percentage of nitrogen in the fertilizer compound,[2] and the efficiency by which the application method and time increases the nitrogen supply in the soil. Gross revenue, on the other hand, is a function of the projected crop price multiplied by the projected yield. Yield is, to some degree, dependent on available moisture and total nitrogen supply (including added nitrogen). For a summary of these dependencies see Figure 1.

---

[1] A discussion of how to determine the optimal return will be given later in the paper.

[2] Fertilizer compounds may contain up to four nutrients, each accounting for a percentage of a fertilizer's total composition.

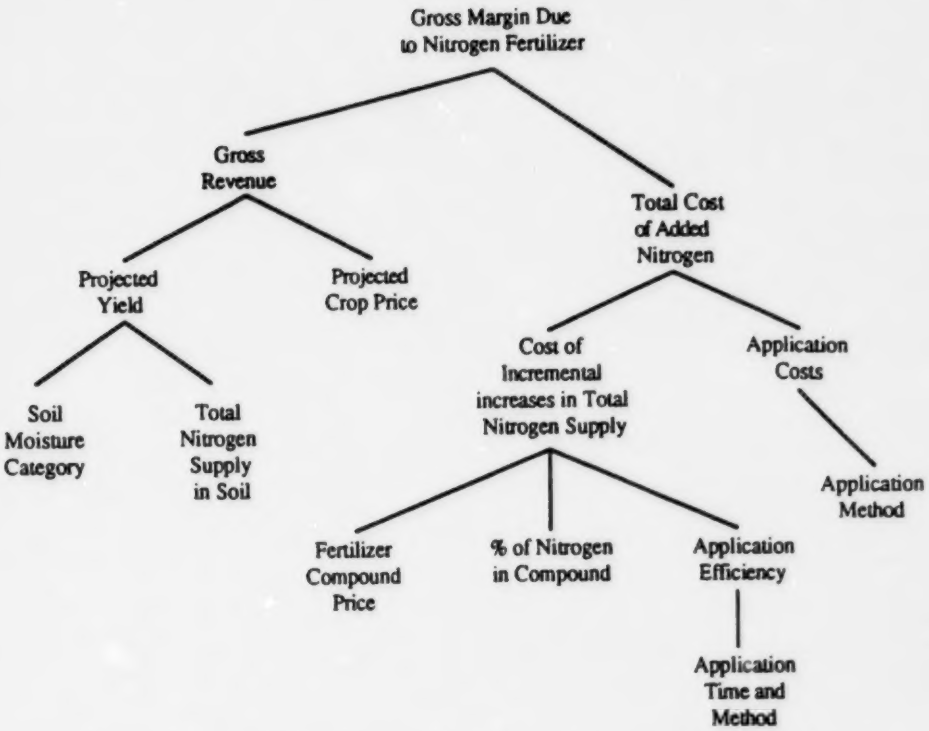

Gross Margin Due to Nitrogen Fertilizer
Gross Revenue
Total Cost of Added Nitrogen
Projected Yield
Projected Crop Price
Cost of Incremental increases in Total Nitrogen Supply
Application Costs
Soil Moisture Category
Total Nitrogen Supply in Soil
Application Method
Fertilizer Compound Price
% of Nitrogen in Compound
Application Efficiency
Application Time and Method

Figure 1: Task overview for a given level of existing nitrogen supply in soil.

The task of determining the optimum yield—the yield that will provide the greatest margin of returns over fertilizer costs—is complex. Generally, yield is described as a function of nitrogen supply as depicted in Figure 2. The curve describing the yield at each increment of nitrogen can be derived in one of two ways. First, a complex equation based on such variables as water supply, nitrogen supply, and growing degree days could be used to plot a continuous curve. However, to the best of our knowledge no equation exists that can be used to accurately plot the yield response of any crop. Second, a tabular approach based on observations of multiple trials under similar conditions can be used to estimate the response for set increments in nitrogen supply. The second alternative, a tabular approach, has been adopted for use in the FSA system. This approach, when illustrated graphically, results in a segmented curve. However, for illustrative purposes, the curve has been smoothed.

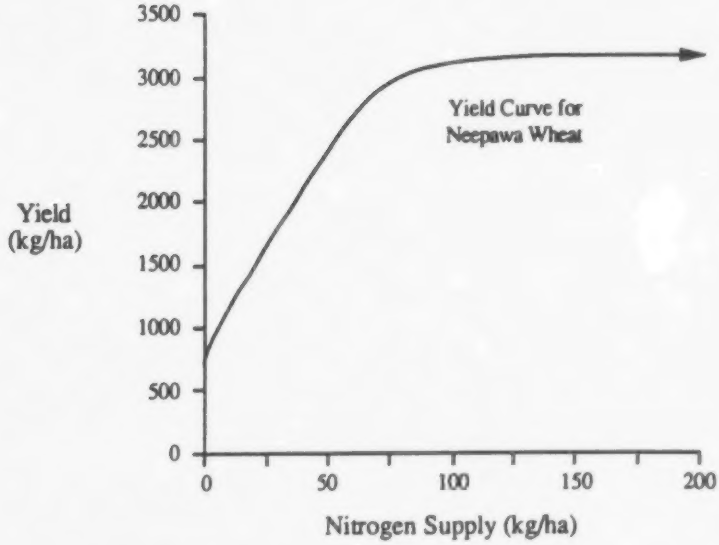


Figure 2: A yield curve for Neepawa wheat under moist growing conditions.

The specific values used for plotting the yield response curves are taken from the Yield/Nitrogen Supply Tables used by the Manitoba Provincial Soil Testing Laboratory (see Figure 3). For each cereal crop there are four separate tables; one for each of four moisture regimes (*i.e.*, arid, dry, moist, and irrigated). Each table describes the average expected yield (kg/ha) for increments of total nitrogen supply in the soil. The FSA prototype uses slight modifications to these tables.

Nitrogen Supply	(kg/ha)	Yield
0		800
10		1120
20		1440
30		1760
40		2080
50		2400
60		2675
70		2860
80		2980
90		3060
100		3100
110		3140
120		3180
130		3180

Figure 3: Example of a yield table for Neepawa wheat under moist growing conditions

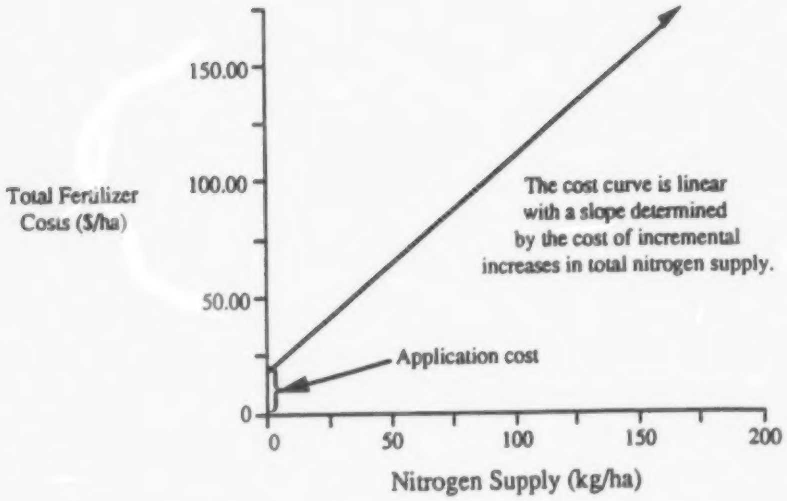


Figure 4: Example of a cost curve for one type of fertilizer and one application method.

The second step in determining the optimum yield involves establishing a corresponding fertilizer cost curve. The cost curve for the application of one fertilizer using one method is linear (see Figure 4). A simple cost curve can be calculated by determining the cost of adding one increment of nitrogen using a specific application method and time, and a single fertilizer compound.

The final fertilizer cost curve may not be linear; the cost curve may involve splicing together portions of several cost curves to achieve the cheapest cost curve. The resulting cost curve may involve multiple application methods (*e.g.*, due to a fertilizer exceeding toxicity constraints when applied using one particular method) and possibly several fertilizer compounds (see Figure 5). The process of calculating such a cost curve is complex due to the exponential nature of the possible combinations of fertilizers and application methods. An intelligent search strategy is employed in the FSA prototype to constrain the possibilities and thus reduce the amount of search that must be performed in calculating the final cost curve.

The objective of the decision making process is to construct a fertilization plan that produces the optimum yield. The FSA system is designed to screen the relevant information on fertilizer and application costs and efficiencies, developing a table of

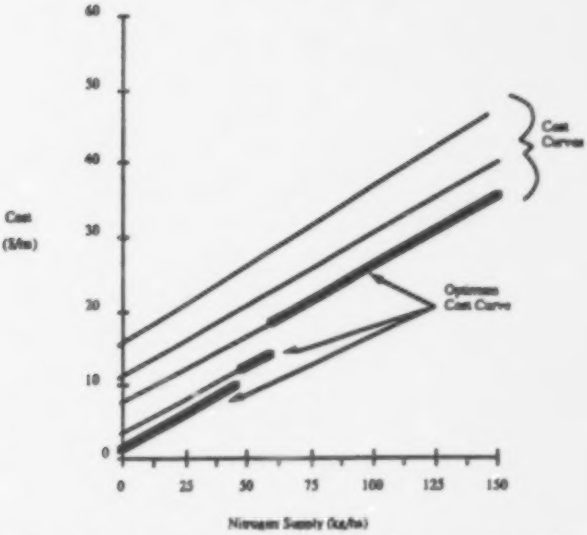


Figure 5: Example of a cost curve for multiple fertilizers and application methods.

information describing gross revenue as a function of the least cost combination of fertilizers and application methods. Combinations that do not result in the least cost for a particular level of nitrogen supply in the soil are disregarded, except in cases where other constraints (*e.g.* toxic limits for applying a certain fertilizer with the seed) must be considered. Once completed, the cost curve is superimposed on the yield curve, and the point at which the distance between the two curves is greatest marks the maximum net returns for that fertilizer and application method (see Figure 6).

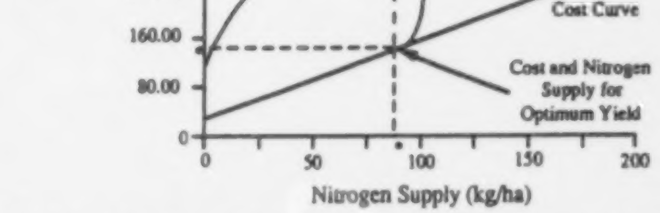


Figure 6: A fertilization cost curve superimposed on a revenue curve. The revenue curve is the yield curve from Figure 2, multiplied by a price of $160.00 per tonne.

4 PROBLEM FORMULATION

In AI terms, the fertilizer problem is best characterized as a planning problem with constraints [Evans et al., 1989]. The crux of the problem involves generating a plan that details:

i) what specific fertilizer compound(s) to apply;
ii) when to apply the fertilizer(s);
iii) how to apply the fertilizer(s); and
iv) in what amounts to apply the fertilizer(s).

When establishing this plan, a variety of constraints need to be taken into account, such as the toxicity limits of fertilizer compounds, the cost of applying the fertilizer (including application costs and prices of the various compounds), and individual preferences (a farmer may have limited resources, including time, machinery, and capital). The goal of the FSA system is to develop a cost effective plan while abiding by these constraints.

In order to construct a fertilizer plan, the system requires extensive knowledge describing available actions, anticipated consequences of actions, and alternative courses of action. In the FSA prototype, knowledge is represented by objects. Objects may be physical objects that can be seen or touched (*e.g.* fertilizers, machinery) or abstract categories (*e.g.* application methods, moisture categories). We have organized the knowledge into three general categories of objects: fertilizers, application methods, and client data. By using this approach we were able to structure the domain knowledge and represent each object's physical and behavioral characteristics (see Figure 7).

Name: Urea
Price per tonne: $250.00
Price per kg: $0.250 Price per kg of N: $0.543

Nitrogen: 46.0% expressed as % by weight
Phosphorous: 0.0%
Potassium: 0.0%
Sulfur: 0.0%

Available in the following forms:

Gas: NO Liquid: NO Granular: YES

Toxicity: 30.00 (max. kg of N/ha, in a seed row)

Figure 7: Representation of a fertilizer compound.

The behaviors of objects are represented using procedures and rules embedded in the system. Procedures contain knowledge about behaviors which are known and accepted facts in the domain. Such procedures are hard-coded into the system. Rules in the system's rulebase contain heuristic knowledge which our domain expert has acquired from experience. For example, the effects of soil conditions on the toxicity constraints associated with various fertilizer compounds are represented as IF-THEN action statements in our rulebase. When the rules are invoked, these statements will adjust the toxicity constraints of the applicable fertilizer compounds accordingly (see Figure 8).

IF	the fertilizer being considered is Urea or UAN Solution
	and
	client's soil condition is dry or client's soil texture is coarse
THEN	the fertilizer should not be applied in the seed row
BECAUSE	under these soil conditions the fertilizer is likely to cause a toxic reaction and destroy the seed.

Figure 8: A sample toxicity rule.

The system also needs case-specific data to formulate a plan when considering a particular user's situation. Data is made available via two sources: the user and data tables. The user may supply information that is specific to his/her scenario, such as soil nutrient levels, soil type, crop variety, and application preferences, or allow the system to use standard default values. User information varies for each problem. Data tables are used to store information that may vary occasionally, but not quite so often as user supplied data. Examples of data tables include: yield response tables for a variety of cereal crops, regional precipitation tables, and tables containing the market price for the different varieties of grain.

5 IMPLEMENTATION

When the implementation phase of the FSA development project first began, no concrete decisions had been made concerning development tools. We began by exploring a variety of commercially available software packages designed for building expert systems in a microcomputer environment. After experimenting with several of these packages, we concluded that these tools did not sufficiently cover the necessary facilities identified during the problem formulation stage. In particular, the packages provided very restrictive reasoning mechanisms and only limited means for incorporating conventional computing facilities[1]. The FSA system was originally developed on a Macintosh microcomputer using a dialect of Common LISP; however, the system has since been converted to an IBM platform (the prevalent machine of the end-users) using the C language[2]. C requires much less computing resources (e.g. memory and CPU) than Lisp and is becoming a popular alternative for AI programming, particularly in microcomputer environments. User interface routines, and rulebase management routines have been developed by computer science graduate students at the University of Manitoba using C. The availability of these routines combined with the flexibility and speed offered by C are the main advantages which prompted us to choose C over other development software.

The FSA prototype consists of five main components: a front-end for interfacing with the user, a processing component, an explanation subsystem, a rulebase, and data tables (see Figure 9). The user interface provides the system with a means of requesting data from the user, responding to questions posed by the user, and displaying intermediate and final results. The processing component uses information supplied by the user, domain knowledge, knowledge embedded in the rulebase, and internal data tables to formulate recommendations. At any point during a consultation, questions the user may have concerning the system's recommendations may be directed towards the explanation subsystem (*e.g.*, explanations of various toxicity constraints encountered).

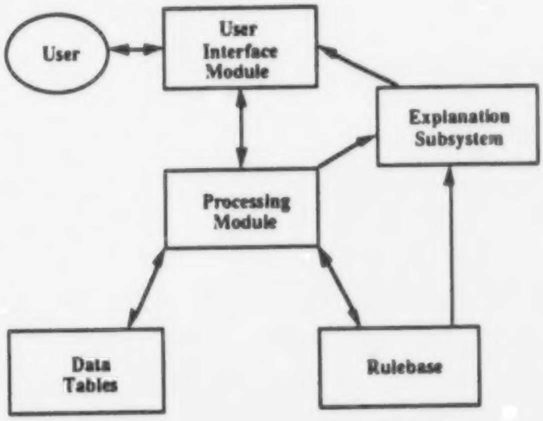


Figure 9: Components of the FSA system.

---

[1] The reader should note that these types of software packages often can be very useful in developing expert systems; in our case, however, the packages available in our price range were not well-suited to our problem.

[2] An alternative is to use C++, an object-oriented version of the C programming language. C++ may be used in future versions of the FSA system.

The operation of the system's processing component is divided into four separate phases: rulebase processing, pre-processing, main processing, and post-processing (see Figure 10). The rulebase processing phase strengthens or weakens some of the default constraint values based on information entered by the user. Client information entered is used by the rulebase to modify the fertilizer and/or application method information. The information is tailored to the particular farm situation being considered rather than to all farms in one geographic area. This allows the system to work with more appropriate information in the later phases of processing.

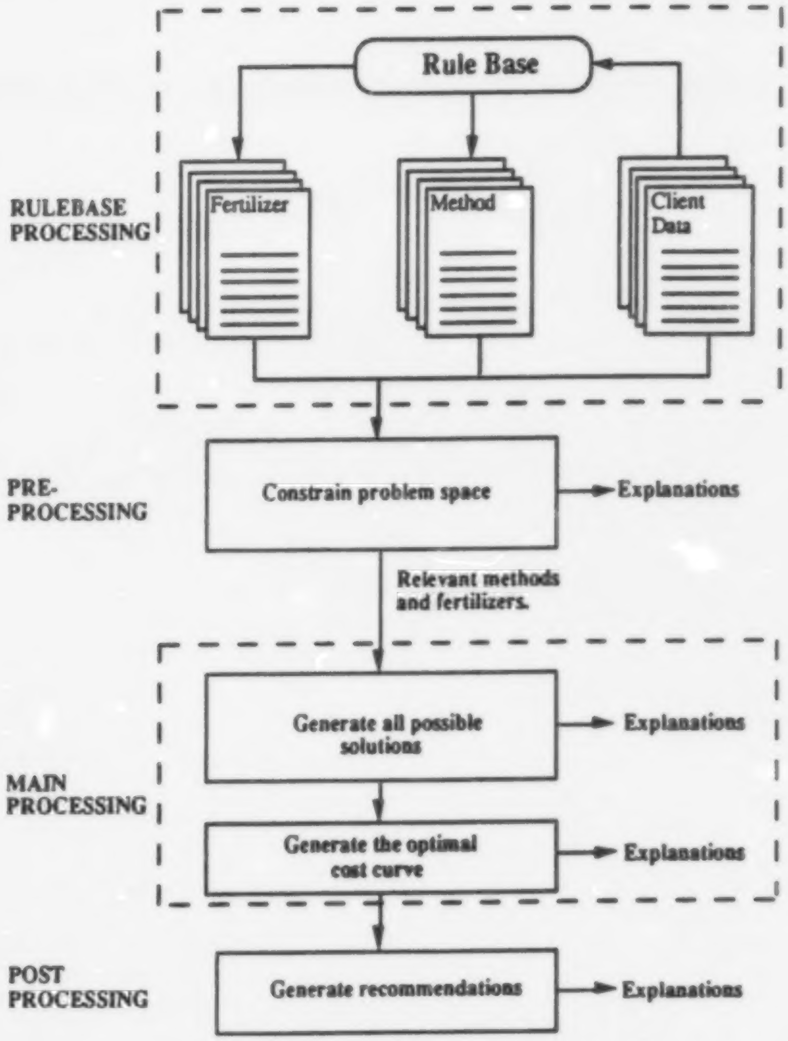

Rule Base
Fertilizer
Method
Client Data
RULEBASE PROCESSING
PRE-PROCESSING
Constrain problem space
Explanations
Relevant methods and fertilizers.
MAIN PROCESSING
Generate all possible solutions
Explanations
Generate the optimal cost curve
Explanations
POST PROCESSING
Generate recommendations
Explanations

Figure 10: Processing component phases.

The pre-processing phase constrains the problem space to a manageable size. During this phase, all application method and fertilizer compound combinations are formed. The possibilities (*i.e.*, application methods and fertilizer compounds) which will not be applicable to the specific problem are pruned out. For example, the user may instruct the system to consider only a subset of the possible application methods, due to availability of machinery. Other constraints are not quite so intuitively obvious and may require extensive processing (such as, the pruning of entire subsets of possibilities which incur high costs due to cost constraints). This phase plays an important role in the success of the system because it utilizes domain knowledge to reduce the problem space which in turn reduces the search necessary in the next processing phase. A sample of the resulting list of application method and fertilizer combinations from the pre-processing phase is given in Figure 11.

Application Method with **Efficiency Rate** and **Application Cost**

Associated Fertilizers *with* ***Price per kg***

Banded With Seed	60%	$0.00	
Urea		*$0.54/kg*	*(KEPT)*
AM Nitrate		*$0.66/kg*	*(KEPT)*
UAN		*$0.57/kg*	*(PRUNED)*
Spring Banded	60%	$15.00	
Anhydrous Ammonia		*$0.44/kg*	*(KEPT)*
Urea		*$0.54/kg*	*(PRUNED)*
UAN		*$0.57/kg*	*(PRUNED)*
AM Nitrate		*$0.66/kg*	*(PRUNED)*
Spring Broadcast	50%	$7.50	
Anhydrous Ammonia		*$0.44/kg*	*(KEPT)*
Urea		*$0.54/kg*	*(PRUNED)*
UAN		*$0.57/kg*	*(PRUNED)*
AM Nitrate		*$0.66/kg*	*(PRUNED)*
Fall Banded	**47%**	**$15.00**	**(**PRUNED**)**
Anhydrous Ammonia		*$0.44/kg*	*(KEPT)*
Urea		*$0.54/kg*	*(PRUNED)*
UAN		*$0.57/kg*	*(PRUNED)*
AM Nitrate		*$0.66/kg*	*(PRUNED)*

Explanation:

Fall Banding need not be considered because in this scenario Spring Banding will always be chosen over Fall Banding when selecting least cost application method alternatives since Spring Banding is more efficient and is less costly.

Figure 11. The result from the pre-processing phase. KEPT indicates possibilities which will be considered by the main processing phase

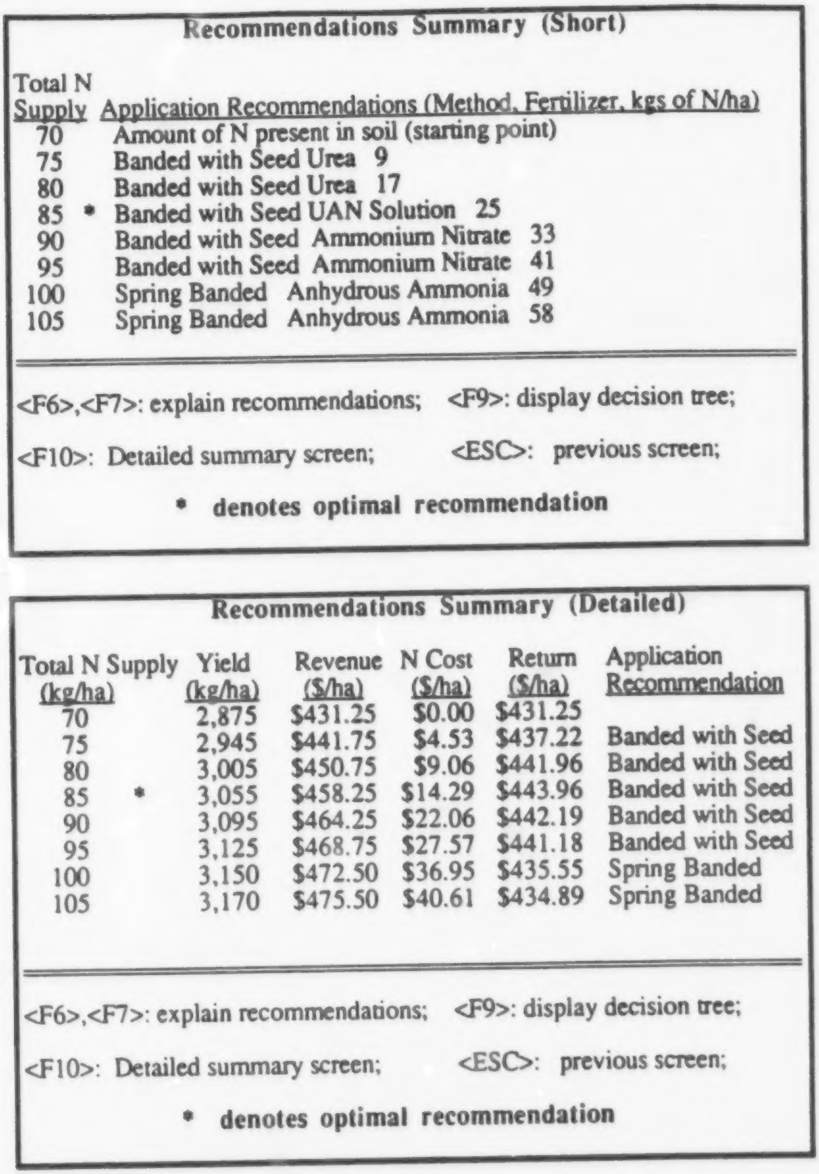
The user can request explanations of the constraints and processing used during preprocessing by querying the explanation subsystem as illustrated in Figure 11.

The main processing phase consists of two steps. The first step involves generating the (reduced) problem space of all possible potential solutions. The second step performs the actual search of the problem space. The search performed during this phase is known as a *constraint-directed search* [Fox, 1987]. Constraints introduced during the search process constrain the search space and reduce the necessary search time [Newell et al, 1976].[1] An example of a constraint that is often encountered during the search process is a fertilizer toxicity limit. When considering the possibility of adding a fertilizer compound to the seed row, toxicity constraints govern the amount of fertilizer that can be added before damage to the seed occurs. The search algorithm must recognize these toxicity constraints and not surpass them when recommending the amount of fertilizer to apply. Consequently, the system searches along the curves as illustrated in Figure 6, generating the appropriate recommendation at each 5 kg/ha increment of N and also locating the point of greatest distance between the revenue and the cost curve (i.e., the optimal solution).

During post-processing, a summary list of potential solutions is presented to the user with the most cost effective alternative being highlighted. Such recommendations are available in two level of details. A short recommendation summary (see Figure 12) simply lists at each 5 kg/ha increment of N, the recommended application method and the amount of the corresponding fertilizer compound. A more detailed recommendation summary lists for each 5 kg/ha increment of N, the method (or combination of methods) that should be used to apply the fertilizer, the fertilizer compound (or compounds) that should be applied under each method, the cost per hectare of applying the fertilizer, the additional revenue generated as a result of applying that fertilizer, and the forecasted profit margin. At both levels of detail, an explanation is available to display the complete set of information associated with the recommendation at each 5 kg/ha increment of N. Although not currently available, future development will incorporate a graphical display of the reasoning used in finding the optimal solution, similar to that in Figure 6.

---

[1] This technique is commonly used to solve planning problems.



```
                 Recommendations Summary (Short)

Total N
Supply  Application Recommendations (Method, Fertilizer, kgs of N/ha)
  70      Amount of N present in soil (starting point)
  75      Banded with Seed Urea  9
  80      Banded with Seed Urea  17
  85  *   Banded with Seed UAN Solution  25
  90      Banded with Seed  Ammonium Nitrate  33
  95      Banded with Seed  Ammonium Nitrate  41
 100      Spring Banded  Anhydrous Ammonia  49
 105      Spring Banded  Anhydrous Ammonia  58
═══════════════════════════════════════════════════════════════════
<F6>,<F7>: explain recommendations;   <F9>: display decision tree;

<F10>:  Detailed summary screen;        <ESC>:  previous screen;

               * denotes optimal recommendation
```

```
                 Recommendations Summary (Detailed)

Total N Supply   Yield     Revenue   N Cost   Return    Application
   (kg/ha)      (kg/ha)    ($/ha)    ($/ha)   ($/ha)    Recommendation
     70          2,875    $431.25    $0.00   $431.25
     75          2,945    $441.75    $4.53   $437.22    Banded with Seed
     80          3,005    $450.75    $9.06   $441.96    Banded with Seed
     85      *   3,055    $458.25   $14.29   $443.96    Banded with Seed
     90          3,095    $464.25   $22.06   $442.19    Banded with Seed
     95          3,125    $468.75   $27.57   $441.18    Banded with Seed
    100          3,150    $472.50   $36.95   $435.55    Spring Banded
    105          3,170    $475.50   $40.61   $434.89    Spring Banded
═══════════════════════════════════════════════════════════════════
<F6>,<F7>: explain recommendations;   <F9>: display decision tree;

<F10>:  Detailed summary screen;        <ESC>:  previous screen;

               * denotes optimal recommendation
```

Figure 12: Two levels of solution details.

6 SUMMARY

We have found this application to be well-suited to expert systems technology because the problem relies heavily on knowledge describing the relevant factors involved in selecting fertilizers. In addition, the incremental development methodologies used to create expert systems allowed us to gradually expand the scope of the system's knowledge and thus control the complexity surrounding the decision making involved in generating fertilizer recommendations. Furthermore, we were able to program the system with sufficient knowledge enabling it to focus its attention towards relevant information only, thus reducing the problem space to a manageable size and significantly improving the efficiency of the system. Another key benefit of expert systems, the ability to explain the decision making process, was also incorporated into the FSA prototype. This facility allows the users to query the system about the decision making process, thus providing the users with a better understanding of the underlying assumptions, facts, and reasoning used to generate recommendations.

The construction of the FSA prototype has demonstrated the feasibility of applying expert system technology and techniques to a single farm management task. The prototype is being expanded in depth (*i.e.*, adding the capability to handle economic and environmental factors such as climate and weather patterns, fertilizer storage costs, and a wider spectrum of farm-specific information) as well as breadth (*i.e.*, developing recommendation modules for handling other nutrients: sulphur, potassium, and phosphorus). We are currently developing an architecture to incorporate these features by extending our original constraint-based approach to utilize a community of cooperating agents each capable of reasoning about particular subsets of the factors involved in analyzing and planning fertilizer recommendations.

Our initial work has demonstrated successfully that expert systems technology can be used in conjunction with conventional computing techniques to extend the level of decision support that can be provided in agricultural applications. It is our belief that this trend will continue in the future with even greater success.

References

[Buchanan et al., 1983] B.G. Buchanan, D. Barstow, R. Bechtal, J. Bennett, W. Clancey, C. Kulikowski, T. Mitchell, and D. A. Waterman, *Constructing an Expert System*, in "Building Expert Systems", Addison-Wesley, Reading, Massachusetts, 1983.

[Davis et al., 1982] R. Davis, and D.B. Lenat, *Knowledge-Based Systems in Artificial Intelligence*, McGraw-Hill, New York, 1982.

[Evans et al., 1989] M. Evans, R. Mondor, and D. Flaten, *Expert Systems and Farm Management*, CAEFMS Farm Management Workshop, Winnipeg, 1989 (also to appear in *Canadian Journal of agricultural Economics*).

[Fox, 1987] M. Fox, *Constraint-Directed Search: A Case Study of Job-Shop Scheduling*, Morgan-Kaufmann Publishers, Los Altos, California, 1987.

[Harmon, 1985] P. Harmon and D. King, "Expert Systems", John Wiley & Sons, New York, 1985.

[Luger et al., 1989] G. F. Luger and W. A. Stubblefield, "Artificial Intelligence and the Design of Expert Systems", Benjamin/Cummings, California, 1989.

[McNurlin, 1988] *Trends in Artificial Intelligence*, ed. B.C. McNurlin, I/S Analyzer, No. **2**, **26**(1988).

[Miller, 1986] A. Miller, *Expert Systems: The Structure, history, and future of successful AI applications*, IEEE Potentials, (October 1986).

[Newell et al., 1976] A. Newell and H.A. Simon, *Computer Science as Empirical Inquiry: Symbols and Search*, Communications of The ACM, No. **3**, **19**(1976).

[Waterman, 1986] D.A. Waterman, "A Guide to Expert Systems", Addison-Wesley, Reading, Massachusetts, 1986.

CROP ROTATIONS ON THE CANADIAN PRAIRIES

C.A. Grant[1], L.D. Bailey[2], C.A. Campbell[3], R.P. Zentner3,
H.H. Janzen[4] and K.E. Bowren[5]
Agriculture Canada, Brandon[1] Ottawa[2], Swift Current[3],
Lethbridge[4] and Melfort[5]

A crop rotation is a planned sequence of crops grown in recurring succession on the same area of land. Crop rotations play an important role in ensuring optimum productivity. The benefits of crop rotations include improved resistance to soil erosion and degradation, improved soil fertility and soil tilth, enhanced aggregate stability, increased availability of stored moisture, improved pest control, reduction of allelopathic or phytotoxic effects, enhanced economic stability, and more even distribution of work load.

There are three primary criteria for selecting cropping sequences:

1. Economic viability
2. Long-term effect on soil productivity
3. Impact on the environment

Based on these criteria, the effectiveness of cropping practices can be adequately evaluated only in long-term experiments. However, most agronomic experiments are relatively short-term. This tends to over-emphasize immediate short-term economics to the exclusion of long-term effects on soil productivity and the environment.

The objective of long-term rotation studies was to identify cropping practices for western Canada prairie conditions which ensure long-term economic viability, soil productivity and environmental quality. In order to do this, more than 68 long-term crop rotation studies have been conducted at Agriculture Canada Research Stations throughout western Canada. These stations were located throughout the various soil zones (Fig. 1) and covered a range of environmental conditions (Table 1). Twenty crop rotation studies are still on-going, some dating back to 1910. The results of studies from the

Table 1. Soil and climatic conditions of major sites

Site	Soil[1] zone	Annual precip (mm)	Annual deficit (mm)	Growing deg. days (>5°C)	Mean temp (°C)
Swift Current, Sask.	Brown	334	395	1675	3.3
Scott, Sask.	Dk. Brown	355	280	1442	1.0
Lethbridge, Alta.	Dk. Brown	413	268	1689	5.0
Indian Head, Sask.	Black	427	180	1633	2.0
Brandon, Man.	Black	485	145	1705	1.9
Melfort, Sask.	Black	411	95	1468	0.3
Lacombe, Alta.	Black	443	65	1334	2.1
Beaverlodge, Alta.	Dk. Gray	467	3	1221	1.6

[1] Brown = Aridic Boroll; Dark Brown = Typic Boroll; Black = Udic Boroll; Dark Gray = Boralfic Cryoboroll; Gray = Alfisol

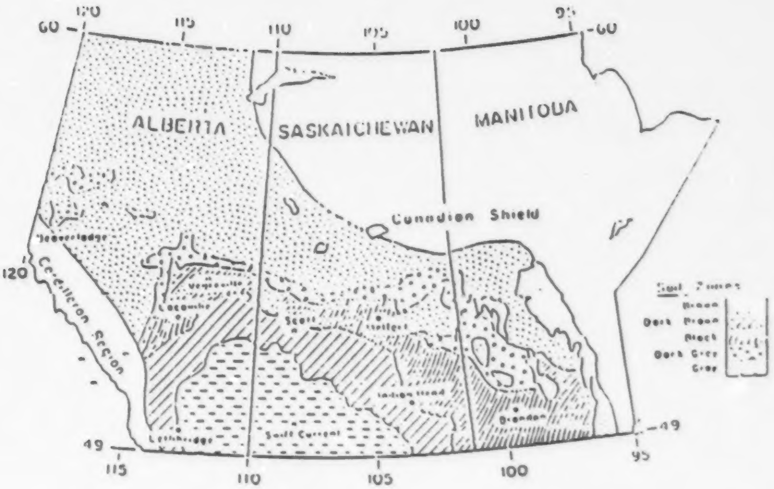

120
115
110
105
100
95
60
60
ALBERTA
SASKATCHEWAN
MANITOBA
Canadian Shield
Beaverlodge
120
Cordilleran Region
Vegreville
Lacombe
Scott
Melfort
Indian Head
Brandon
Lethbridge
Swift Current
Soil Zones
Brown
Dark Brown
Black
Dark Grey
Grey
49
49
115
110
105
100
95

Figure 1. Major soil zones of the prairie region.

last 20 years were compiled, summarized and integrated for formation of agronomic recommendations.

This information is being released early in 1990 in the form of two publications - a pamphlet for free distribution (Zentner et al. 1990) and a more detailed book (Campbell et al. 1990) which will be available for purchase.

Observations and Recommendations

The choice of crop rotations by the producer is influenced by physical and environmental factors, including soil and climatic constraints, incidence of pests and intercrop interactions. These factors determine crops which can be grown and the expected yields. Economically, summerfallow remains a justifiable option for the semi-arid regions of western Canada. As fallowing frequency increases, negative effects on soil quality increase (Table 2). Organic matter content, microbial activity, enzyme activity and soil aggregation all decrease with increased fallowing. The negative effects of fallowing on soil quality can be reduced by minimizing fallow frequency in the rotation, reducing tillage or using alternative fallow systems such as annual legume green manures.

Although inclusion of fallow in the semi-arid Brown and Dark Brown soil zones enhances nèt returns, frequent fallowing has little economic benefit in the moister Black and Gray soils (Fig. 2). At Melfort, net income for continuous wheat ranked lowest because of problems with weeds and disease. At Brandon, studies of crop rotations between 1965 and 1970 that included various fallow

Table 2. The influence of fallowing frequency on organic C content, total N content, C/N ratio, potentially mineralizable N content (N_o), and potentially mineralizable N as a proportion of total N

Location	Duration (depth)	Rotation Sequence	Organic Matter Characteristics					Fertilizer	Source
			Organic C (%)	Total N (%)	C/N	N_o (mg kg^{-1})	N_o/total (%)		
Brown Soil Zone									
Swift Current	1967-1982 (0-7.5 cm)	Cont. W	2.15	0.226	9.5	230	10.2	N,P	Biederbeck et al. 1984
		F-W-W	1.70	0.189	9.0	197	10.4	N,P	
		F-W	1.94	0.202	9.6	159	7.9	N,P	
Dark Brown Soil Zone									
Lethbridge	1912-1975 (0-13 cm)	Cont. W	1.91	0.17	11.2	-	-	none	Dormaar and Pittman 1980
		F-W-W	1.55	0.15	10.6	-	-	none	
		F-W	1.36	0.12	10.9	-	-	none	
Lethbridge	1951-1984 (0-15 cm)	Cont. W	1.78	0.180	9.9	133	7.4	none	Janzen 1987
		F-W-W	1.58	0.160	9.8	105	6.5	none	
		F-W	1.50	0.156	9.6	68	4.3	none	
Black Soil Zone									
Indian Head	1958-1984 (0-7.5 cm)	Cont. W	2.43	0.198	12.3	-	-	none	Campbell (unpublished)
		F-W-W	2.25	0.186	12.1	-	-	none	
		F-W	2.21	0.179	12.3	-	-	none	
Melfort	1957-1984 (0-75. cm)	Cont. W	5.92	0.532	11.1	-	-	none	Campbell (unpublished)
		F-W-W	5.30	0.501	10.6	-	-	none	
Solonetzic Soil									
Vegreville (Ap)	1958-1980	Cont. W	4.24	0.34	12.5	55	2.2	N,P	Carter 1984
		F-W	3.79	0.25	15.7	95	2.8	N,P	

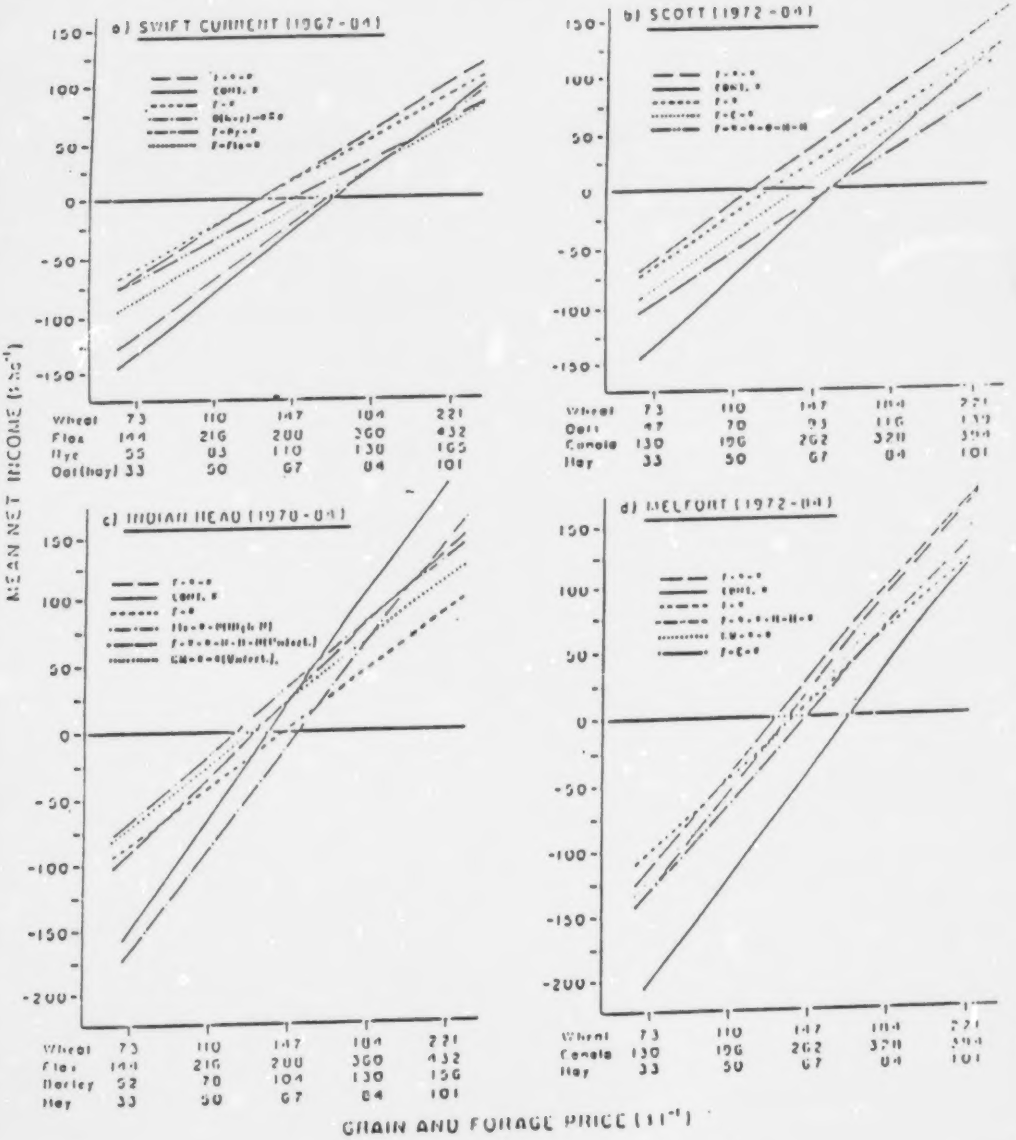


Figure 2. Effect of product prices on net income for selected rotations at Swift Current, Scott, Indian Head, and Melfort.

substitute crops found little economic value from including a high proportion of summerfallow in the rotation, especially in the sandy loam soil (Table 3). Potatoes were highly profitable and clover hay, corn, oat hay and flax were also equally or more profitable than summerfallowing once every third year.

Perennial forages are recommended for inclusion in rotations in sub-humid soils. On the Gray and Black soils, where severe moisture stress is not normally a problem, perennial forages such as alfalfa can enhance soil quality by input of biologically fixed nitrogen. In these soils, perennial forages can have pronounced and prolonged residual benefits on yields of subsequent crops (Table 4). In the experiment shown in Table 4, the advantages of alfalfa and bromegrass-alfalfa over grasses and fallow were still evident in the tenth wheat crop (data not shown).

Table 3: Mean net income for six crop rotations at Brandon (1965-70) (From Spratt et al. 1975).

Rotation sequence	Clay loam soil ($ ha^{-1})	Sandy loam soil ($ ha^{-1})
F-W-W	45	10
CL(hay)-W-W+	55	20
P-W-W	173	101
C-W-W	45	17
O(hay)-W-W	49	17
Flx-W-W	42	12

+ Based on 1970 prices and costs.

Table 4: Yields of wheat grown successively after a fallow-wheat rotation or forage species that had produced hay for two to six years on a Gray Luvisol at McLennan, Alberta (From Hoyt and Hennig 1971).

Fallow wheat control and preceding forage	Mean wheat yields kg ha^{-1}				
	Crop 1	Crop 2	Crop 4	Crop 5	Crop+ 5
Fallow wheat (control)	1320	840	640	1050	2220
Red fescue	670	690	910	1210	2580
Bromegrass	680	580	880	1300	2780
Alfalfa	2260	2530	1120	1760	2770
Bromegrass-alfalfa	1990	1160	1060	1570	2740

+ 56 kg N ha^{-1} applied.

In the semi-arid Brown and Dark Brown soils, perennial forages appear to have little benefit on crop yields or soil quality. The absence of effect is attributed to depletion of the soil moisture reserves.

Preceding crops in the rotation play a prominent role in maintaining soil moisture and pest control. Soil moisture depletion is generally greater after cereal crops than after oilseeds such as flax and canola. On average, only about 10% of the moisture received during a 21 month period is stored in the soil in the Black and Gray soil zones. In the Brown and Dark Brown soil zones, the figure increases to 18-20%. Because of this, stored moisture often influenced yields in the drier zones but rarely in the Black and Gray soil zones.

Crops which are poor competitors with weeds, such as flax, are very susceptible to weed infestations. This may lead to weed problems in subsequent crops. Continuous cereals may lead to infestations of grassy weeds. Use of mixed forage-cereal rotations tended to suppress weeds in the Black and Gray soils. Summerfallow and intertilled cropping systems led to the least weed problems.

Diseases such as common root rot in wheat and blackleg in canola require at least a 3-yr break from susceptible crops to reduce infestation on host crops. Sclerotinia in canola requires even longer break periods. Since this disease also attacks flax, pulse crops, clover and alfalfa, break crops must be cereals or grasses. The dry conditions common to the Brown and Dark Brown soil zones and the inherent disease resistance of hard red spring wheats help to minimize disease problems in these regions.

Application of fertilizer, based on soil test recommendations promotes profitability in the rotation and can improve soil quality. Fertilization at recommended rates increases net income in all soil zones, particularly in rotations with low frequency of fallow or legumes (Fig. 3). Fertilization enhances moisture use efficiency by the stimulation of root growth. Nitrogen fertilization also increases organic matter concentration, mineralizable N content and microbial activity (Table 5). The effect appears to be less pronounced when organic matter content of the soil is higher. Prolonged use of N fertilizers at moderate rates reduces soil pH (0.3 to 0.5 units) but not sufficiently to cause immediate concern.

The progressive decline in soil quality with continued cultivation is not inevitable. Results of rotation studies consistently confirmed the degradative effects of frequent fallow on soil quality, evidenced by loss of organic matter, depreciation of organic matter quality, reduced microbial activity, and enhanced susceptibility to erosion. In long-term rotations dating back to 1910, organic C concentrations fell sharply immediately after initial cultivation. However, they have since rebounded to approach original levels (Fig. 4). The recovery of N concentrations requires the input of fertilizers or other N amendments.

Crop yields in the various crop rotations have generally increased over time, perhaps partly because of technological advances. Soil productivity can be maintained or even improved through the judicious use of legumes, animal manures, or fertilizers and by the elimination of degradative influences such as excessive tillage or frequent fallowing.

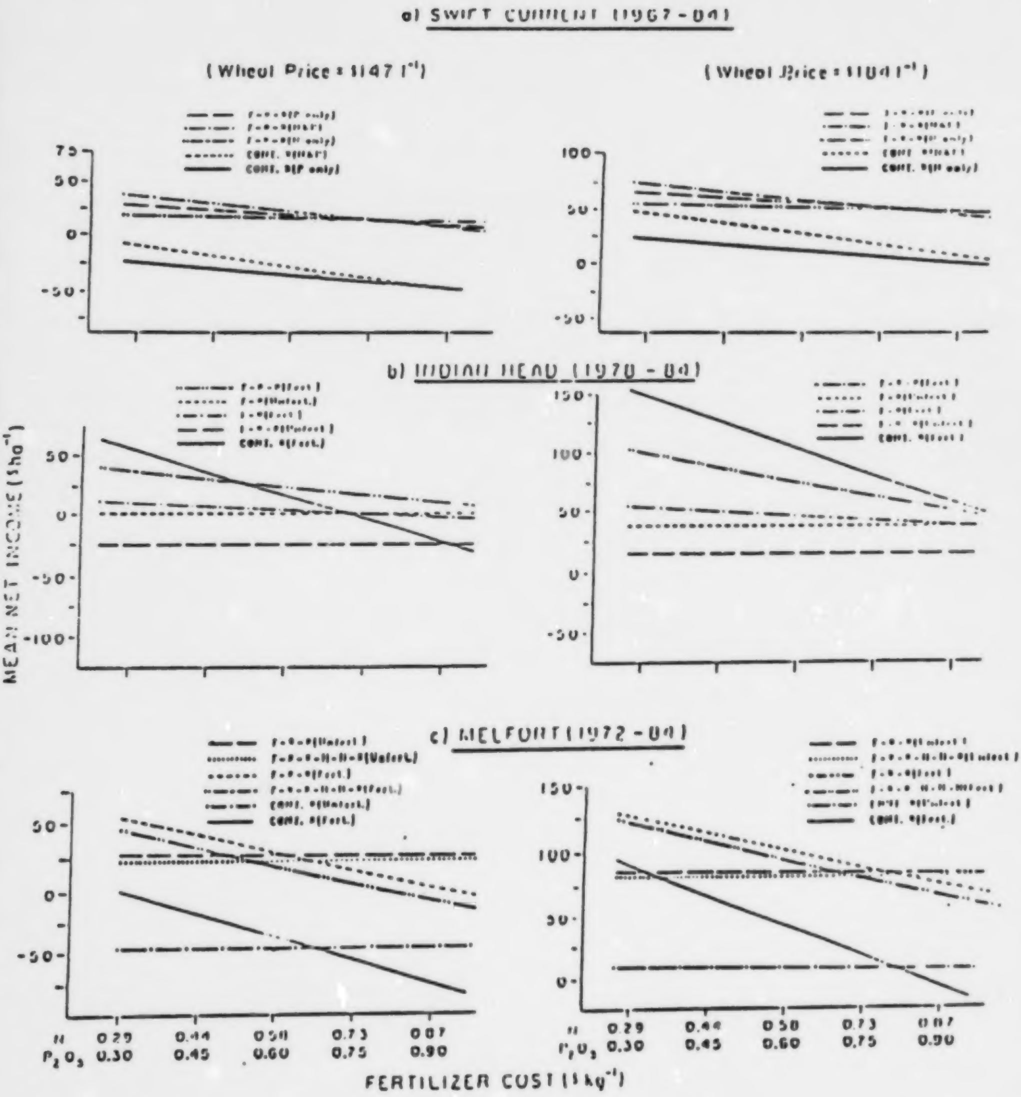


Figure 3. Effect of wheat price and fertilizer cost on net income from fertilization.

Table 5. The influence of fertilizer application on organic C content, Total N content, C/N ratio, potentially mineralizable N content (N_o), and potentially mineralizable N as a proportion of total N

				Organic Matter Characteristics					
Location	Duration (depth)	Rotation	Fertilizer treatment	Organic C (%)	Total N (%)	C/N	N_o (mg kg^{-1})	N_o/total (%)	Source
Brown Soil Zone									
Swift Current	1967-1982 (0-7.5 cm)	Cont. W	P	1.78	0.197	9.0	185	9.4	Biederbeck et al. 1984
			N+P	2.15	0.226	9.5	230	10.2	
Dark Brown Soil Zone									
Lethbridge	1912-1975 (0-13 cm)	F-W-W	none	1.43	0.141	10.3	151	10.7	Janzen (1987)
			P	1.46	0.138	10.6	140	10.1	
			N	1.67	0.155	10.7	207	13.4	
			N+P	1.64	0.141	10.6	213	15.1	
		Cont. W	none	1.62	0.149	10.9	192	12.9	
			P	1.61	0.141	11.5	221	15.7	
			N	1.80	0.162	11.1	255	15.7	
			N+P	1.88	0.171	11.0	250	14.6	
Black Soil Zone									
Indian Head	1958-1984 (0-7.5 cm)	F-W	none	2.21	0.179	12.3	-	-	Campbell (unpublished)
			N+P	2.28	0.186	12.2	-	-	
		F-W-W	none	2.25	0.186	12.1	-	-	
			N+P	2.38	0.200	11.9	-	-	
		Cont. W	none	2.43	0.198	12.3	-	-	
			N+P	2.59	0.223	11.6	-	-	
Melfort	1957-1984 (0-7.5 cm)	F-W-W	none	5.30	0.501	10.6	-	-	Campbell (unpublished)
			N+P	5.04	0.498	10.1	-	-	
		Cont. W	none	5.92	0.527	11.2	-	-	
			N+P	6.02	0.532	11.3	-	-	

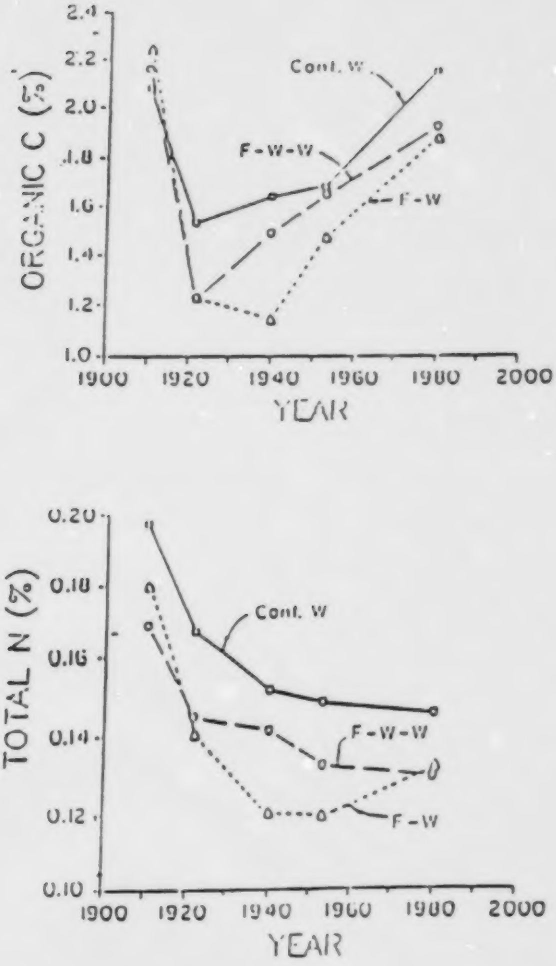
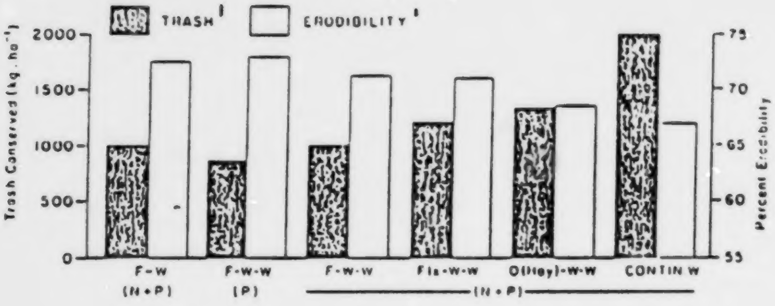


Figure 4. Temporal changes in (a) organic C concentration and (b) total N concentration in an unfertilized Dark Brown Chernozemic soil at Lethbirdge as influenced by crop rotation (From Freyman et al. 1982).

The effect of cropping on environmental quality is influenced by agronomic variables. Soil erodibility can be minimized by reducing fallowing frequency, adjusting tillage timing and frequency, application of optimum fertilizer levels and adoption of other cropping practices which favor the production and conservation of crop residues (Fig. 5).



* Based on % of soil diameter < 0.42 mm

† Based on % of soil diameter < 0.84 mm, samples taken from top 5 cm of soil

‡ Based on average of 5, 1 m^2 samples per plot

Figure 5. The influence of crop rotation and fertilizer application on erodibility (% of soil with aggregate diameter < 0.84 mm) and trash conservation in a Brown Chernozemic soil at Swift Current (From Biederbeck et al. 1984).

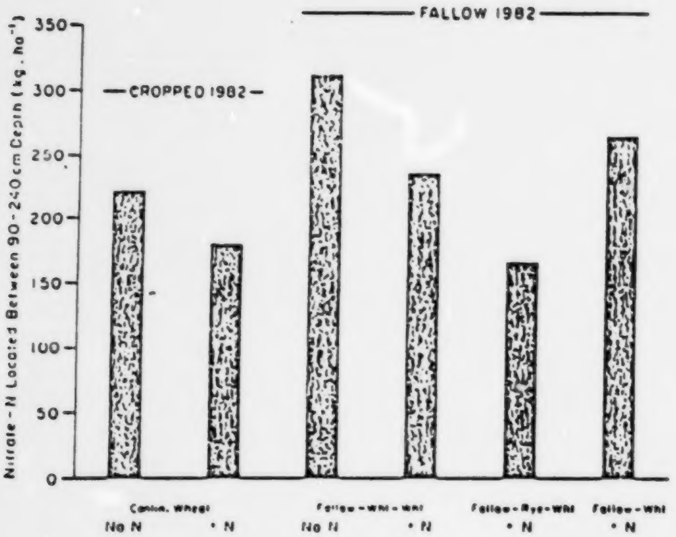


Figure 6. Subsoil nitrate-N in Brown Chernozem at Swift Current as influenced by crop rotation and fertilizer application (From Campbell et al. 1984).

Nitrate leaching can be reduced by minimizing fallowing frequency and by using fall-sown crops. Moderate fertilizer applications may also reduce leaching losses, by stimulating root growth and sub-soil N recovery (Fig. 6).

Although long-term crop rotation studies provide valuable information, they do have a number of important limitations. The studies that were initiated early in the century are unreplicated, so statistical analysis is a problem. Conduct of crop rotation studies is expensive and time consuming. Because of resource and logistical constraints, only a limited number of crops have been included in long-term studies. Agronomic practices evolve with time due to developments in technology. If practices in the study are changed, there can be confounding effects; if they are not changed, the study loses relevance to current conditions. Finally, research sites are few compared to the variability in the soil and climatic conditions that exists on the prairies. However, in spite of these problems, rotation studies can make an important contribution to our understanding of the long-term effects of crop management on the plant-soil system.

REFERENCES

Biederbeck, V.O., C.A. Campbell and R.P. Zentner. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in south-western Saskatchewan. Can. J. Soil Sci. 64: 355-367.

Campbell, C.A., R. de Jong and R.P. Zentner. 1984. Effect of cropping, summerfallow and fertilizer nitrogen on nitrate-nitrogen lost by leaching on a Brown Chernozemic loam. Can. J. Soil Sci. 64: 61-74.

Campbell, C.A., Zentner, R.P. Janzen, H.H. and Bowren, K.E. 1990. Crop rotation studies on the Canadian Prairies. Agriculture Canada publication (In press).

Carter, M.R. 1984. Effect of soil management on some chemical, physical and biological properties of a solonetzic soil. Soil Sci. 138: 411-416.

Dormaar, J.F. and U.J. Pittman. 1980. Decomposition of organic residues as affected by various dryland spring wheat-fallow rotations. Can. J. Soil Sci. 60: 97-106.

Freyman, S., C.J. Palmer, E.H. Hobbs, J.F. Dormaar, G.B. Schaalje and J.R. Moyer. 1982. Yield trends in long-term dryland rotations at Lethbridge. Can. J. Plant Sci. 62: 609-619.

Hoyt, P.B. and A.M.F. Hennig. 1971. Effect of alfalfa and grasses on yield of subsequent wheat crops and some chemical properties of a Gray-Wooded soil. Can. J. Soil Sci. 51: 177-183.

Janzen, H.H. 1987. Soil organic matter characteristics after long-term cropping to various spring wheat rotations. Can. J. Soil Sci. 67: 845-856.

Spratt, E.D., J.H. Strain and B.J. Gorby. 1975. Summerfallow substitutes for western Manitoba. Can. J. Plant Sci. 59: 685-689.

Zentner, R.P., Campbell, C.A., Janzen, H.H. and Bowren, K.E. 1990. Benefits of crop rotation for sustainable agriculture in dryland farming. Agriculture Canada bulletin (In press).

Effectiveness of Urea and Reactive Layer Coated Urea in Field and Greenhouse Experiments.

G.Morden and C.M.Cho

Urea is a major form of nitrogen applied in Manitoba (1988-89, 24% of fertilizer N sales). However, there are some difficulties with urea, in particular volatilization of the ammonia.

Influencing ammonia volatilization are soil properties such as pH and H^+-buffering capacity which mark the potential for loss. In terms of magnitude, environmental factors such as soil water, temperature and air exchange govern the loss under field conditions. Management factors such as method and rate of application also affect the process.

There are a number of solutions which have been applied to reduce the magnitude of loss:
1- making fertilizer products with a low pH.
2- slowing down the enzymatic hydrolysis of urea with inhibitors.
3- using coated urea.

People are familiar with the idea of coated urea, but usually as sulphur coated urea. In this experiment we used plastic coated urea, referred to as Reactive Layer Coated Urea (RLCU). This particular plastic coated urea was supplied to us by IFDC.

Table 1. Reactive Layer Coated Urea

code		Supplied by	Total N	7 Day Dissolution Rate %
#10	Polyurethane	IFDC *	42	16
#11	Coated		44	42
#12	Urea		44	60
#13			44	88

* IFDC International Fertilizer Development Center

RLCU Reactive Layer Coated Urea

Dr. Christianson of IFDC has done incubation studies on this material which showed that the N release rate of RLCU increased with increasing temperature and decreased coating thickness. He noticed a slight effect of soil moisture, but it was not pronounced. As opposed to sulphur coated urea, it appears that the coating is not susceptible to microbial activity.

To look at the usefulness of RLCU in Manitoba, both a growth chamber experiment and a field experiment were conducted, using N15 enriched fertilizers. We examined the yield values and the 'A' value, in order to evaluate the RLCU. The 'A' value is a measure of the nutrient supply in terms of available units of applied fertilizer, is yield independent and requires the N15 enrichment of the fertilizer.

The field site was at St. Claude, a Willowcrest gleyed orthic black chernozem. The treatments were done on a completely randomized block design. There was one urea treatment and four different RLCU, based on coating thickness, applied at a rate of 50 kg N/ha. There were two methods of application, broadcast and banded. In both cases the N15 labelled urea, applied at a rate of 20 kg N/ha, was placed in a shallow trough on both sides of the centre row. This means that there are three sourses of N for the plant, N15 labelled urea, the added fertilizer and the soil. The crop, Columbus wheat, was harvested at maturity and the entire plant was ground and analyzed.

There was no significant difference between the banded and the broadcast treatments, therefore, the results of the two treatments were combined.

Table 2. Results from the field experiment

Treat.	Mean Yield (t/ha)	Mean % N15 (excess)	A value (kg/ha)	A value of RLCU (kg/ha)
urea	1.90 a	.234 a	194 a	50
#10	2.32 b	.297 b	148 b	4
#11	1.75 a	.274 b	162 b	18
#12	1.83 a	.302 b	145 b	2
#13	1.81 a	.295 b	149 b	6

During the year the crop was subjected to drought conditions and the yields indicated inconsistent differences between the urea and RLCU treatments. However, measurement of N15 and the 'A' value calculation indicated that the RLCU treatment derived less of its N from the fertilizer than did the urea treatment.

Because the N15 was higher in the RLCU treatments, the plants were taking more from the labelled fertilizer and less from the RLCU.

In a growth chamber experiment, RLCU was compared to urea using various soils varying in texture, pH and organic matter.

The soils were a St. Claude, Wellwood, Glenlea and an Organic - 5 kg of soil were sieved through a 2mm sieve. (note on organic soil, it was used without pretreatment at 40% moisture content - dry weight of 1100 gm, then brought to approximentally 300% field capacity.)

As in the field experiment the crop was Columbus wheat.

50 kg N/ha equivalent of fertilizer, both urea and the RLCU, were added

and 20 kg N/ha equivalent of urea N15 was applied as a solution (2.5% N15)

The pots were filled to within 5 cm of the surface and brought to near field capacity. Fertilizer pellets were uniformly distributed across the surface and the urea N15 was sprayed on as evenly as possible. The rest of the soil was added and brought to about 80% of field capacity for the mineral soils. Other nutrients were applied as solutions. 10 seeds were placed in each pot - 1 cm from the surface and one week later thinned to 5 plants. Pots were in a randomized split plot design.

The whole plant sample was analyzed for Yield, %N15 and the 'A' value was calculated.

Table 3. Yield for the Growth Chamber Experiment (gm/pot)

	St. Claude	Wellwood	Glenlea	Organic	Overall
Urea	8.61	12.43	9.38	3.58	8.61
#10	8.99	13.90	9.76	4.61	8.99
#11	10.14	14.83	9.69	5.43	10.02
#12	9.70	14.69	9.61	4.79	9.70
#13	8.84	13.76	10.65	4.61	9.47
LSD 5%	1.56	2.44	1.60	1.18	0.78
LSD 1%	2.27	3.54	2.33	1.72	1.05

Table 4. %N15 excess for the Growth Chamber Experiment

	St. Claude	Wellwood	Glenlea	Organic	Overall
Urea	0.370	0.097	0.261	0.252	0.245
#10	0.322	0.085	0.232	0.230	0.217
#11	0.305	0.099	0.233	0.221	0.215
#12	0.306	0.094	0.223	0.223	0.211
#13	0.321	0.094	0.235	0.220	0.218
LSD 5%	0.016	0.017	0.016	0.024	0.008
LSD 1%	0.023	0.025	0.023	0.036	0.011

Table 5. 'A' value for the Growth Chamber Experiment

	St. Claude	Wellwood	Glenlea	Organic	Overall
Urea	115	499	171	179	241
#10	135	569	196	198	274
#11	144	490	195	207	259
#12	143	515	205	204	267
#13	136	512	193	207	262
LSD 5%					21
LSD 1%					28

The yields from the RLCU treatments were higher than the yields for the urea treatment. The %N15 in plants grown on the urea treatment was higher than from plants grown on the RLCU. The 'A' value was lower in the plants grown on the urea than the plants grown on the RLCU, in contrast to the field experiment. This indicates that the utilization of N from the RLCU was higher than the utilization of N from urea.

Summarizing the effect of these of these two experiments:
Using the 'A' value to compare the effectiveness of the RLCU to the urea.

Fertilizer	Field (kg/ha)	Growth Chamber (kg/ha)
Urea	50	50
RLCU #10	4	83
RLCU #11	18	68
RLCU #12	2	76
RLCU #13	6	71

Even though we do not know the true effectiveness of the urea, the data can be normalized to urea, set urea equal to 50, to allow comparisons.

Our conclusion from these results was that under regular to excellent moisture conditions, RLCU appears superior to urea, however, under dry conditions, RLCU is inferior to the urea.

Yield and Nitrogen Uptake by Wheat and Canola Fertilized with Urea and an Urease Inhibitor, Phenylphosphorodiamidate

D. L. DeBeer and J. C. Yeomans, University of Manitoba

ABSTRACT

To determine the effects of an urease inhibitor, phenylphosphorodiamidate (PPD), on early plant growth, nitrogen uptake, and crop yields, wheat and canola were grown in growth chamber experiments, in growth pouches and in pots. Both wheat and canola have similar urease activity, however, the wheat plants were able to grow in growth pouches with urea as their only nitrogen source while the canola plants were stressed under similar conditions. When the plants were forced to grow with urea plus PPD, the wheat plants showed browning of the leaf tips and the canola plants showed severe nitrogen stress. Similar results were not obtained when the plants were grown in nitrate plus PPD. All plants were analyzed during the early stages of growth to determine the forms of nitrogen present in the tissue. Plants treated with urea plus PPD or with nitrate plus PPD contained detectable amounts of urea. In the pot experiment, plants treated with urea or urea plus PPD had lower yields than those treated with nitrate or nitrate plus PPD. Yields of both wheat and canola were statistically lower when treated with urea plus PPD than when treated with nitrate plus PPD. These results suggest that there is an interaction of urea and PPD in the plant tissue which is detrimental to plant growth.

INTRODUCTION

The growing importance of urea (NH_2CONH_2) as a fertilizer in world agriculture can be attributed to its advantages over other nitrogen (N) fertilizers. These advantages include high nitrogen content (45-46% in fertilizer-grade material); low cost of manufacture, transportation, storage, and distribution; high solubility in water; and ease of handling (no fire or explosion hazard). Moreover, urea is suited for production of compound fertilizers as well as for use in pellets with various pesticides and urease inhibitors.

Although urea has these important advantages as a N fertilizer, there are problems associated with its use. These problems result largely from the rapid hydrolysis of urea to ammonia and carbon dioxide by soil urease and the concomitant rise in pH and accumulation of ammonium. The problems include damage to germinating seedlings and young plants, nitrite and/or ammonium toxicity, and gaseous loss of urea-N as ammonia (Gasser, 1964; Tomlinson, 1970). Gaseous losses of urea fertilizer N as ammonia is of particular concern because they can exceed 50% of the fertilizer N applied (Catchpoole, 1975; Terman, 1979). Also, the combination of high ammonium concentration and high pH resulting from the rapid hydrolysis of urea by soil urease retards microbial oxidation of nitrite to nitrate (Aleem and Alexander, 1960; Alexander, 1965).

One approach to reducing the problems associated with the use of urea fertilizers is to find compounds that will inhibit urease activity and thereby retard the hydrolysis of urea when applied to soils in conjunction with this fertilizer.

Two such compounds have been developed that will effectively retard urea hydrolysis in soil, phenylphosphorodiamidate (PPD) and N-(n-butyl)thiophosphoric triamide (NBPT) (Matzel et al., 1979; Bremner and Chai, 1986). However, researchers have been unable to show a statistically significant crop yield increase when these inhibitors are used in the field with urea (Byrnes et al., 1983; Broadbent et al., 1985; Tomar et al., 1985; Fillery et al., 1986; Rao and Ghai, 1986; Schlegel et al., 1986; Buresh et al., 1988a; Buresh et al., 1988b).

The objective of our research was to determine the effects of an urease inhibitor, PPD, on early plant growth, nitrogen uptake, and crop yield of wheat and canola grown in growth chamber experiments. The study involved determining the ability of these crops to hydrolyze urea, the forms of nitrogen these crops can use for tissue growth, and the levels of different forms of nitrogen in young plant tissues fertilized with different forms of nitrogen with and without the urease inhibitor.

MATERIALS AND METHODS

-Barley (Hordeum vulgare cv. Argyle), navy bean (Phaseolus vulgaris cv. Seaforth), canola (Brassica napus cv. Westar), sweet corn (Zea mays cv. Golden Beauty), flax (Linum usitatissimum cv. NorMan), and wheat (Triticum aestivum cv. Columbus) plants were grown for three weeks in the growth chamber. Plant shoots were harvested, chopped fresh, and analyzed for urease activity (Frankenberger and Tabatabai, 1982).

Wheat and canola were grown in growth pouches with six N treatments: (1) nitrate (NO_3^-), (2) NO_3^- plus PPD, (3) urea, (4) urea plus PPD, (5) NO_3^-plus urea (6) NO_3^- plus urea plus PPD. Seeds were surface sterilized with ethanol and sodium hypochlorite, and then rinsed with partially sterilized, distilled water. The seeds were placed in growth pouches that contained a 40 mL solution with the various N treatments. For the first two treatments, a Hoagland's solution containing NO_3^- as the sole source of N was used (Tuite, 1978). The NO_3^- was applied at a rate of 210 μg N mL-1. For treatments 3 and 4, the $Ca(NO_3)_2$ and KNO_3 in the Hoagland's solution were replaced by $CaCl_2$ and K_2SO_4, respectively, and N was applied as urea at the rate of 210 μg mL-1. In treatments 5 and 6, the solution was a Hoagland's solution plus 210 μg urea-N mL^{-1}. The PPD was added at a rate of 1% of urea (4.5 μg PPD mL^{-1}). The experiment was arranged in a completely randomized design with three replications.

The seeds in the pouches were incubated in the dark for 6 days at 15°C. Once the seeds had germinated, the pouches were placed in a growth chamber set at a 16 h day (22°C), 8 h night (15°C) cycle. The pouches received distilled water daily to maintain ~40 mL of solution per pouch.

The plants were harvested two weeks after emergence. The shoots were separated from the roots, and the plant tissues were dried at 65°C for 48 h, weighed (for dry matter yields), ground, extracted with KCl-PMA, and the extractants were analyzed for tissue concentrations of urea-N, NH_4^+-N, NO_2^--N, and NO_3^--N.

The dry matter yields were statistically analyzed using the GLM procedure (Goodnight et al., 1988).

Wheat and canola were also grown in a growth chamber experiment using a Carberry silt loam soil (pH = 5.6, total N = 5.03 g kg^{-1}, organic C = 73.2 g kg^{-1}). The soil was sieved (<2 mm) in the field moist condition, and 2500 g (oven-dry basis) of soil was treated with a basal nutrient solution containing 100 μg K g^{-1} and 40 μg S g^{-1} as K_2SO_4 and 20 μg P g^{-1} as H_3PO_4, and placed in 3 L pots. Nitrogen treatments were applied 2.5 cm below the seeds, which were planted to a depth of 0.5 cm. The four N treatments were (1) NO_3^-, (2) NO_3^- plus PPD, (3) urea, and (4) urea plus PPD. The PPD was added at a rate of 1% of urea (3.2 μg PPD mL^{-1}). The experiment was arranged in a completely randomized design with five replications.

The pots were placed in a growth chamber set at a 16 h day (22°C), 8 h night (15°C) cycle. The soil in the pots was moistened to 2/3 field capacity with distilled water. The pots were maintained at 2/3 field capacity (by weight) by adding distilled water to the soil surface daily. The pots were thinned to 4 plants per pot three weeks after emergence and were side dressed with 100 μg N g^{-1} soil as KNO_3 five weeks after emergence.

The wheat and canola plants were grown to maturity, harvested, dried at 65°C, and weighed for straw and grain yields.

The results were statistically analyzed using the GLM procedure (Goodnight et al., 1988).

RESULTS AND DISCUSSION

Six crops (barley, navy beans, canola, sweet corn, flax, and wheat) were analyzed to determine their ability to hydrolyze urea (Table 1). From the data, it is shown that both wheat and canola have about the same level of urease activity and that they hydrolyze urea at a rate similar to other crops that have been tested (Frankenberger and Tabatabai, 1982).

For the wheat and canola grown in growth pouches, yields of shoot and root tissue from the various treatments are reported in Table 2. Both crops were able to grow adequately with NO_3^-, urea, or NO_3^- and urea as the N sources. The canola plants did show N stress when urea was the only N source, however, it did not affect the total shoot weight at harvest. Inclusion of PPD with the NO_3^- treatment did not affect the growth of the plant and the wheat plants grown with this treatment had significantly more shoot tissue than the other two treatments which received PPD (Table 2). However, when PPD was included with urea as the N source, with or without NO_3^-, the wheat plants showed tip burning of the leaves. This phenomenon was also observed by Bremner and Krogmeier (1988) when they grew barley, oats, sorghum, and wheat with urea and PPD or with another urease inhibitor, NBPT [N-(n-butyl)thiophosphoric triamide]. Eskew et al. (1983) suggested that the necrosis

Table 1. Urease activity of fresh shoots of various plants.

Plant	Urease activity[†]
Sweet corn	10.6
Canola	74.0
Wheat	84.6
Navy beans	94.6
Barley	117.2
Flax	120.2

[†] μg NH_4^+-N produced/ 0.1 g plant material (oven-dry basis)/2 h (37°C).

resulted from an accumulation of toxic concentrations of urea.

When canola was grown with the urea plus PPD treatment, the plants grew poorly and showed the lowest weight of shoot and root tissue (Table 2). Nitrogen stress of canola plants was also evident in the NO_3^- plus urea plus PPD treatment. The tip burning of the wheat leaves and the N stress in the

Table 2. Yield of shoot and root tissue of wheat and canola grown in growth pouches.

	Wheat		Canola	
Treatment	Shoot	Root	Shoot	Root
	mg pouch^{-1}			
NO_3^-	305 ab[†]	168 a	150 a	43 ab
NO_3^- + PPD	350 a	202 a	116 ab	30 bc
Urea	337 ab	144 a	140 ab	54 a
Urea + PPD	227 c	130 a	78 b	13 c
NO_3^- + Urea	290 b	181 a	125 ab	40 ab
NO_3^- + Urea + PPD	284 bc	163 a	106 ab	22 bc

[†] Numbers for each crop and each tissue, followed by the same letter, are not significantly different at the 0.05 level.

canola plants in treatments containing urea and PPD suggests that there is a reaction between the urea and the PPD, and this is somehow detrimental to plant growth.

After harvest, the plant shoot and roots were analyzed for urea-N, NH_4^+-N, NO_2^--N, and NO_3^--N (Tables 3 and 4). Regardless of treatment, NO_2^- was

Table 3. Levels of various nitrogen forms in the shoot and root tissue of wheat.

	Shoot N				Root N			
Treatment	Urea	NH_4^+	NO_2^-	NO_3^-	Urea	NH_4^+	NO_2^-	NO_3^-
	μg tissue^{-1}							
NO_3^-	0.0	47.5	0	76.4	0.0	32.2	0	94.3
NO_3^- + PPD	9.9	150.7	0	101.6	0.0	20.7	0	20.3
Urea	0.0	73.1	0	34.2	0.0	19.8	0	30.0
Urea + PPD	99.1	89.6	0	29.5	2.2	38.2	0	14.3
NO_3^- + Urea	0.0	82.0	0	253.2	3.6	68.2	0	321.6
NO_3^- + Urea + PPD	140.6	91.9	0	138.6	14.6	25.4	0	137.6

Table 4. Levels of various nitrogen forms in the shoot and root tissue of canola.

	Shoot N				Root N			
Treatment	Urea	NH_4^+	NO_2^-	NO_3^-	Urea	NH_4^+	NO_2^-	NO_3^-
	μg tissue^{-1}							
NO_3^-	1.7	21.9	0	170.7	0.0	0.0	0	28.2
NO_3^- + PPD	4.5	45.1	0	273.7	0.0	42.3	0	78.8
Urea	0.0	32.8	0	15.5	0.0	0.0	0	0.0
Urea + PPD	71.6	6.2	0	0.0	0.8	0.0	0	0.0
NO_3^- + Urea	4.9	119.1	0	917.2	0.0	32.1	0	108.2
NO_3^- + Urea + PPD	120.2	68.7	0	459.2	4.5	3.9	0	60.6

never detected in any of the shoot or root tissue analyzed. All shoot tissues did contain NH_4^+ ions, but the levels detected did not seem to be affected by the various NO_3^- and urea treatments.

When urea and PPD were included in the treatments, both the wheat and canola accumulated urea in the shoot tissue, and to a lesser extent in the root tissue. The urea accumulation in the shoot and root tissue was accompanied by a decrease in NO_3^- in those tissues, as compared to the same treatments without PPD added (Tables 3 and 4). With urea and PPD included in the treatments, the yields were lower (Table 2) and the shoot and root tissues accumulated urea (Tables 3 and 4) which was not hydrolyzed to forms which could be used for plant growth. This, coupled with plant stress noted in the presence of PPD, suggests that the accumulation of urea in the shoot tissue is due to an inhibition of its hydrolysis, possibly by PPD. Further tests are being conducted to determine if PPD, like urea, is accumulating in the plant tissue.

It is noteworthy that both wheat and canola grown in the NO_3^- plus PPD treatment contained detectable amounts of urea in the shoot tissue. The presence of urea was also accompanied by an increase in shoot tissue NO_3^-, as compared to the treatment containing NO_3^- without PPD. It is known that urea is produced in higher plants through the metabolism of arginine by the enzyme arginase (Beevers, 1976). Urea produced as a result of arginase activity may be degraded by the urease enzyme to ammonia and carbon dioxide. Such a sequence demands the functioning of the urease enzyme. If PPD is accumulating in the plants in treatments with PPD, this would inhibit the function of the urease enzyme, allowing urea to accumulate. This would account for the urea present in the plants, even when urea was not included in the treatment.

Table 5. Grain and straw yield of wheat and canola.

	Wheat		Canola	
Treatment	Straw	Grain	Straw	Grain
	g pot^{-1}			
NO_3^-	22.23 ab[†]	8.14 ab	18.83 ab	5.33 ab
NO_3^- + PPD	22.86 a	8.66 a	19.09 ab	5.08 ab
Urea	21.59 ab	8.36 ab	17.92 ab	5.09 ab
Urea + PPD	20.64 b	7.69 b	17.43 b	5.00 b

[†] Numbers for each crop and each tissue, followed by the same letter, are not significantly different at the 0.05 Level.

The yield data for the growth chamber experiment are reported in Table 5. The plants fertilized with urea plus the urease inhibitor PPD had consistently lower grain and straw yields than the plants grown with the other three treatments. For the wheat, the yields with this treatment were statistically lower than yields obtained when the plants were grown with the NO_3^- plus PPD treatment. These results, like those obtained from the growth pouch experiment, suggest that it is an accumulation of PPD in the plant inhibiting plant urease activity which results in a toxic accumulation of urea. These observations may explain why, although the inhibitor PPD reduces problems associated with the use of the fertilizer urea, PPD applied with urea does not result in a crop yield increase at final harvest.

This research was supported in part by the Natural Sciences and Engineering Research Council of Canada and by the University of Manitoba.

REFERENCES

Aleem, M. I. H., and M. Alexander. 1960. Nutrition and physiology of Nitrobacter agilis. Applied Microbiology 8:80-84.

Alexander, M. 1965. Nitrification. In Soil Nitrogen. (W. V. Bartholomew and F. E. Clark, Eds.). pp. 307-343. American Society of Agronomy, Madison, WI.

Beevers, L. 1976. Nitrogen Metabolism in Plants. Edward Arnold Publishers Ltd., London.

Bremner, J. M., and H. S. Chai. 1986. Evaluation of N-butyl phosphorothioic triamide for retardation of urea hydrolysis in soil. Communications in Soil Science and Plant Analysis 17:337-351.

Bremner, J. M., and M. J. Krogmeier. 1988. Elimination of the adverse effects of urea fertilizer on seed germination, seedling growth, and early plant growth in soil. Proceedings of the National Academy of Sciences, USA 85:4601-4604.

Broadbent, F. E., T. Nakashima, and G. Y. Chang. 1985. Performance of some urease inhibitors in field trials with corn. Soil Science Society of America Journal 49:348-351.

Buresh, R. J., S. K. DeDatta, J. L. Padilla, and M. I. Samson. 1988a. Field evaluation of two urease inhibitors with transplanted lowland rice. Agronomy Journal 80:763-768.

Buresh, R. J., S. K. DeDatta, J. L. Padilla, and T. T. Chua. 1988b. Potential of inhibitors for increasing response of lowland rice to urea fertilization. Agronomy Journal 80:947-952.

Byrnes, B. H., N. K. Savant, and E. T. Craswell. 1983. Effect of a urease inhibitor phenyl phosphorodiamidate on the efficiency of urea applied to rice. Soil Science Society of America 47:270-274.

Catchpoole, V. R. 1975. Pathways of loss of fertilizer nitrogen from a Rhodes grass pasture in south-eastern Queensland. Australian Journal of Agricultural Research. 26:259-268.

Eskew, D. L., R. M. Welch, and E. E. Cary. 1983. Nickel: An essential micronutrient for legumes and possibly all higher plants. Science 222: 621-623.

Fillery, I. R. P., S. K. DeDatta, and E. T. Craswell. 1986. Effect of phenyl phosphorodiamidate on the fate of urea applied to wetland rice fields. Fertilizer Research 9:251-263.

Frankenberger, W. T., and M. A. Tabatabai. 1982. Amidase and urease activity in plants. Plant and Soil 64:153-166.

Gasser, J. K. R. 1964. Urea as a fertilizer. Soils and Fertilizers 27:175-180.

Goodnight, J. H., J. P. Sall, W. S. Sarle, R. D. Tobias, and Y. C. Yuan. 1988. The GLM procedure. In SAS User's Guide: Statistics. pp. 549-640. SAS Institute Inc., Cary, NC.

Matzel, W., H. Lippold, and R. Heber. 1979. Nitrogen uptake and balance of the fertilizers urea, urea with urease inhibitor, and ammonium nitrate applied to spring wheat at stem elongation growth stage. In Isotopes and Radiation in Research on Soil-Plant Relationships. Proceedings IAEA/FAO Symposium, Colombo, Sri Lanka, 1978. pp. 67-82. International Atomic Energy Agency, Austria.

Rao, D. L. N., and S. K. Ghai. 1986. Effect of phenylphosphorodiamidate on urea hydrolysis, ammonia volatilization and rice growth in an alkali soil. Plant and Soil 94:313-320.

Schlegel, A. J., D. W. Nelson, and L. E. Sommers. 1986. Field evaluation of urease inhibitors for corn production. Agronomy Journal 78:1007-1012.

Terman, G. L. 1979. Volatilization of nitrogen as ammonia from surface applied fertilizers, organic amendments and crop residues. Advances in Agronomy 31:189-223.

Tomar, J. S., P. C. Kirby, and A. F. MacKenzie. 1985. Field evaluation of the effects of a urease inhibitor and crop residues on urea hydrolysis, ammonia volatilization and yield of corn. Canadian Journal of Soil Science 65:777-787.

Tomlinson, T. E. 1970. Urea: Agronomic applications. Proceedings - Fertiliser Society London 113:1-76.

Tuite, J. 1978. Natural and synthetic culture media: Fungi. In CRC Handbook Series in Nutrition and Food. Section G: Diets, Culture Media, Food Supplements, Volume III. (M. Rechcigl, Jr., Ed.). pp. 427-504. CRC Press, Inc. Cleveland, OH.

Effects of Nitrapyrin on Corn Yields and Recovery of Ammonium Sulfate at 18 Site-years in Iowa.

M. E. Cerrato, University of Manitoba
A. M. Blackmer, Iowa State University

ABSTRACT

Nitrapyrin [2-chloro-6-(trichloromethyl) pyridine] is a nitrification inhibitor frequently used to prevent losses of nitrogen (N) fertilizer during corn (Zea mays L.) production. Although many studies have shown that nitrapyrin inhibits nitrification in soils, it has not been established that use of nitrapyrin is cost-effective for corn producers in the western portion of the Corn Belt. Field experiments were conducted at 18 site-years from 1985 through 1987 to determine the effects of nitrapyrin on corn yields and recovery of broadcast fertilizer. Ammonium sulfate was applied at four rates (0, 50, 100, and 150 lb N/acre) with and without nitrapyrin and replicated three times. ^{15}N-labeled ammonium sulfate was substituted for unlabeled ammonium sulfate on subplots within yield plots at eight of the site-years. Statistically significant ($P < 0.05$) grain yield responses to fertilizer N were observed at 17 of the 18 site-years. Nitrapyrin significantly increased yields only at 2 of the 72 rate-site-years. Nitrapyrin did not influence recovery of labeled N in grain at 22 of the 24 rate-site-years having labeled fertilizer. It decreased recovery at the other 2 rate-site-years. Nitrapyrin had no significant effect on recovery of labeled N in the soils 8 weeks and 14 months after application. The results suggest that use of nitrapyrin was not cost-effective at any of the sites studied.

INTRODUCTION

Nitrapyrin [2-chloro-6-(trichloromethyl) pyridine] is a nitrification inhibitor often applied with nitrogen (N) fertilizers to improve the efficiency of N fertilization. This compound acts by delaying the transformation of ammonium or ammonium-yielding fertilizers to nitrate and thereby reducing the possibility of N losses by denitrification and leaching. The potential benefits of using nitrification inhibitors have been reviewed frequently (Goring, 1962; Hauck, 1983; Hoeft, 1984; Huber et al., 1977; Keeney, 1980; Meisinger et al., 1980; Parr, 1973). These benefits include increasing the profitability of crop production and decreasing the amounts of fertilizer N that escape from agricultural soils to surface and ground water supplies.

Although it has been clearly established that nitrapyrin is a potent inhibitor of nitrification in soils, it has been difficult to demonstrate that the benefits of this inhibitor justify its cost when used with spring-applied fertilizer for corn (Zea mays L.) production in the western portion of the Corn Belt. Hergert and Wiese (1980) reviewed studies from this region and concluded that there was rather limited corn yield response to nitrification inhibitors. Hoeft (1984) reported an average yield decrease of 1% for spring-applied nitrification inhibitors in 14 studies conducted at the University of Illinois. Hanson et al. (1987) reported data showing that nitrapyrin applied with anhydrous ammonia had no significant effect on grain yields during a four-year study in northeastern Missouri. Blackmer and Sanchez (1988) reported studies from Iowa showing that nitrapyrin applied with anhydrous ammonia had a significant effect on grain yields at only 2 of 12 rate-site-years and that this effect was to decrease yields.

Lack of favorable response to nitrapyrin is difficult to interpret because it may be caused by the ineffectiveness of nitrapyrin or by the inability of the experiment to detect benefits that occurred. Blackmer (1986) presented evidence that most evaluations of nitrapyrin probably lacked adequate experimental sensitivity to detect effects that should be expected if this inhibitor were highly effective in preventing losses of N. Excesses of available N in the soil can obscure the benefits of nitrapyrin. Amid mounting concerns about the economic and environmental costs of N that escapes from agricultural soils, it is important that this inhibitor be evaluated in studies having the ability to distinguish between lack of experimental sensitivity and lack of effect.

Here we report the effects of nitrapyrin on corn yields and recovery of broadcast ammonium sulfate. We reasoned that significant benefits from nitrapyrin were likely with broadcast fertilizers because studies conducted outside the western portion of the Corn Belt (Frye et al., 1981; Huber et al., 1977; Owens, 1981,1987) have shown substantial benefits from nitrapyrin applied with broadcast fertilizers. It seemed likely that greater benefits of nitrapyrin may be observed with broadcast than with banded fertilizers because high concentrations of fertilizer in bands often have inhibitory effects on nitrification. Also, broadcast fertilizers can be applied to experimental plots more accurately than can anhydrous ammonia and, therefore, enable use of experimental designs having adequate sensitivity to detect the probable benefits of nitrapyrin. Fertilizer materials containing either urea or nitrate were not used to avoid possible masking of nitrapyrin effects by leaching of urea or nitrate by heavy rainfalls soon after application. ^{15}N-labeled fertilizers were used to enable determinations of the effects of nitrapyrin on recovery of fertilizer N in soils and plants.

MATERIALS AND METHODS

Six experimental sites were established in 1985 and two additional sites were established in 1986 (Table 1). Plots measuring 15 by 40 ft (six 30-in rows) or 12.7 by 40 ft (four 38-in rows) were established in nonirrigated fields under production agriculture and, except for N application and grain harvest, were managed in accordance with the farmers' normal practices. All plots had been planted to corn the year before the plots were established.

Broadcast ammonium sulfate was spring-applied at four rates (0, 50, 100, and 150 lb N/acre) with and without nitrapyrin in a randomized complete-block design with three replications. Nitrapyrin (N-serve 24E at 1 qt/acre; Dow Chemical Co., Midland, MI) was sprayed on and mixed with the fertilizer immediately before application. For nitrapyrin treatments without fertilizer, nitrapyrin was sprayed on and mixed with a 2-lb sample of soil and the soil was broadcast on the plot. To avoid losses of nitrapyrin by volatilization (Briggs, 1975), nitrapyrin treatments were disked into the soil within 15 min

Table 1. Information describing the experimental sites.

		Soil		
Site	Location	Series	Subgroup	Years studied
1	Marengo	Nevin	Aquic Argiudoll	1985,1986,1987
2	Williamsburg	Mahaska	Aquic Argiudoll	1985
3	Kalona	Bremer	Typic Haplaquoll	1985,1986,1987
4	Iowa City	Mahaska	Aquic Argiudoll	1985
5	Ames 1	Nicollet	Aquic Hapludoll	1985,1986,1987
6	Ames 2	Canisteo	Typic Haplaquoll	1985,1986,1987
7	Ida Grove	Marshall	Typic Hapludoll	1986,1987
8	Holstein	Galva	Typic Hapludoll	1986,1987

after application.

At sites 5 and 6 in 1985 and sites 1, 3, 5, 6, 7, and 8 in 1986, ^{15}N-labeled ammonium sulfate (2 to 4 atom % ^{15}N) with and without nitrapyrin was substituted for unlabeled ammonium sulfate on subplots (7.5 by 7.5 ft for 30-in rows and 7.5 by 9.5 ft for 38-in rows) within the main plots treated with 50, 100, and 150 lb N/acre. These subplots are referred to as ^{15}N subplots and the main plots are referred to as yield plots.

The corn hybrid Pioneer 3475 was planted at all sites except at sites 2, 3, and 4 (Pioneer 3377) and at site 1 in 1987 (Garst 8344). Plant density ranged from 20,250 to 28,350 plants/acre. Grain yields were measured by hand-harvesting 25-ft segments of the two center rows from each plot. The corn was shelled in the field and yields were adjusted to 15.5% moisture content.

Approximately 60 days and 14 months after application of labeled fertilizer in 1986, soil samples were collected from the ^{15}N subplots in three increments (0-6, 6-12, and 12-24 in) to assess the effects of nitrapyrin on the transformations and movement of fertilizer N. For each sample, eight cores (1.25-in dia.) were collected from the ^{15}N subplots, composited, air dried, ground and sieved to pass a 0.08-in screen. The ^{15}N subplots were sampled by using preselected patterns (lines diagonal to corn rows) to avoid collecting cores at the exact same spot at 60 days and 14 months. Recovery of labeled N was determined as described by Sanchez and Blackmer (1988).

Ear leaves (leaves opposite and below the primary ears) were randomly collected from the yield plots (16 leaves from the center two rows) and the ^{15}N subplots (four leaves from the center four plants) when about 75% of the silks had emerged on plots treated with 150 lb N/acre. At physiological maturity, four plants were collected from the center of each ^{15}N subplot and partioned into grain and stover components. All plant materials were dried at 140 °F and ground for analysis. Leaf and stover samples were ground in a Wiley mill to pass a 0.04-in screen, and then ground in a Cyclone mill (Udy model SF, Fort Collins, CO) to pass a 0.02-in screen. Grain samples from yield plots and ^{15}N subplots were dried at 140 °F and ground in a flour mill (Magic Mill III^{+}, Division of SSI, Salt Lake City, UT). The permanganate-reduced iron modification of the Kjeldahl procedure (Bremner and Mulvaney, 1982) was used to determine the total N concentration of samples that had been dried for at least 48 hr at 140 °F.

All statistical analyses were performed by using the GLM procedure as described by Spector et al., 1985.

RESULTS AND DISCUSSION

The amounts of rainfall during the growing seasons in this study were below average in 1985, above average in 1986, and near average in 1987 (Table 2). The amounts of rainfall during the first 8 weeks after N application were much less in 1987 than in 1985 and 1986. Amounts of rainfall during the first 8 weeks after fertilizer application are of special interest because they largely determine the amounts of N lost by leaching and denitrification before this N can be taken up by the crop.

Analysis of soil samples collected 8 weeks after fertilization in 1986 showed that substantial amounts (mean of 40.5%) of fertilizer N were lost from the surface 2-ft layer of soils before plants had an opportunity to take up this N (Fig.1). The amounts of N lost during this wet spring are similar to losses observed in other tracer studies (Cerrato et al., 1985; Priebe, 1988) of the fate of nitrate and urea during wet springs in Iowa. The substantial losses of N that occurred during this year provided nitrapyrin with ample opportunity to prevent losses of N. However, nitrapyrin had no significant ($P < 0.05$) effect on the total amounts of labeled N recovered, whether data from the sites were analyzed individually or combined.

Nitrapyrin also had little effect on the distribution of labeled N among the soil fractions analyzed. Statistically significant increases in amounts of labeled N were found as ammonium at the highest rate of N application at two of the six sites (i. e., $LSD_{0.05}$ values of 3.1 and 5.0 at sites 1 and 8), but the differences were too small to be of practical importance. Nitrapyrin had no significant effect on the amounts of labeled N found in the nitrate-N or the KMI-N (Kjeldahl-minus-inorganic) fractions. The term KMI-N, as defined by Sanchez and Blackmer (1988), is used here because N from both organic matter and nonexchangeable ammonium is included in this fraction and because no attempt was made to distinguish between these forms.

Movement of fertilizer-derived N into the KMI-N fraction was important in this study because an average of 36.5% of the labeled N recovered 8 weeks after N application was present in this fraction. Of course, movement of

Table 2. Amounts of rainfall during the study.

	Amounts of rainfall[†]							
Year	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
	in							
	Within 8 weeks after N application							
1985	12.2	11.9	10.6	11.2	7.2	7.2	NA[‡]	NA
1986	12.4	NA	10.2	NA	9.5	9.5	10.9	10.6
1987	5.5	NA	3.4	NA	4.9	4.9	4.5	4.9
	April through September							
1985	15.8	19.7	16.4	18.0	16.4	16.4	NA	NA
1986	37.5	NA	34.2	NA	33.1	31.1	31.0	27.3
1987	24.2	NA	17.8	NA	28.3	28.3	21.1	22.7
Normal	23.4	24.5	23.1	24.5	23.4	23.4	22.1	21.6
	October through March							
1985	14.1	18.5	17.7	15.6	8.9	8.9	NA	NA
1986	9.4	NA	9.8	NA	9.8	9.8	8.6	9.2
1987	10.8	NA	7.7	NA	8.0	8.0	7.7	9.0
Normal	10.4	9.8	10.8	10.3	8.6	8.6	7.6	7.7

[†] Data collected at nearby locations and compiled by the National Oceanic and Atmospheric Administration 1985,1986,1987.

[‡] NA Not applicable.

fertilizer N into this fraction can be detected only when tracers are used. Our recoveries of labeled N in this fraction are similar to those found (i.e., 30%) by Sanchez (1986) 45 days after application of anhydrous ammonia. Nitrapyrin did not significantly increase the amounts of labeled N in the KMI fraction. Therefore, the results of this study do not support the idea (Ashworth, 1986; Juma and Paul, 1983) that nitrification inhibitors increase net immobilization of

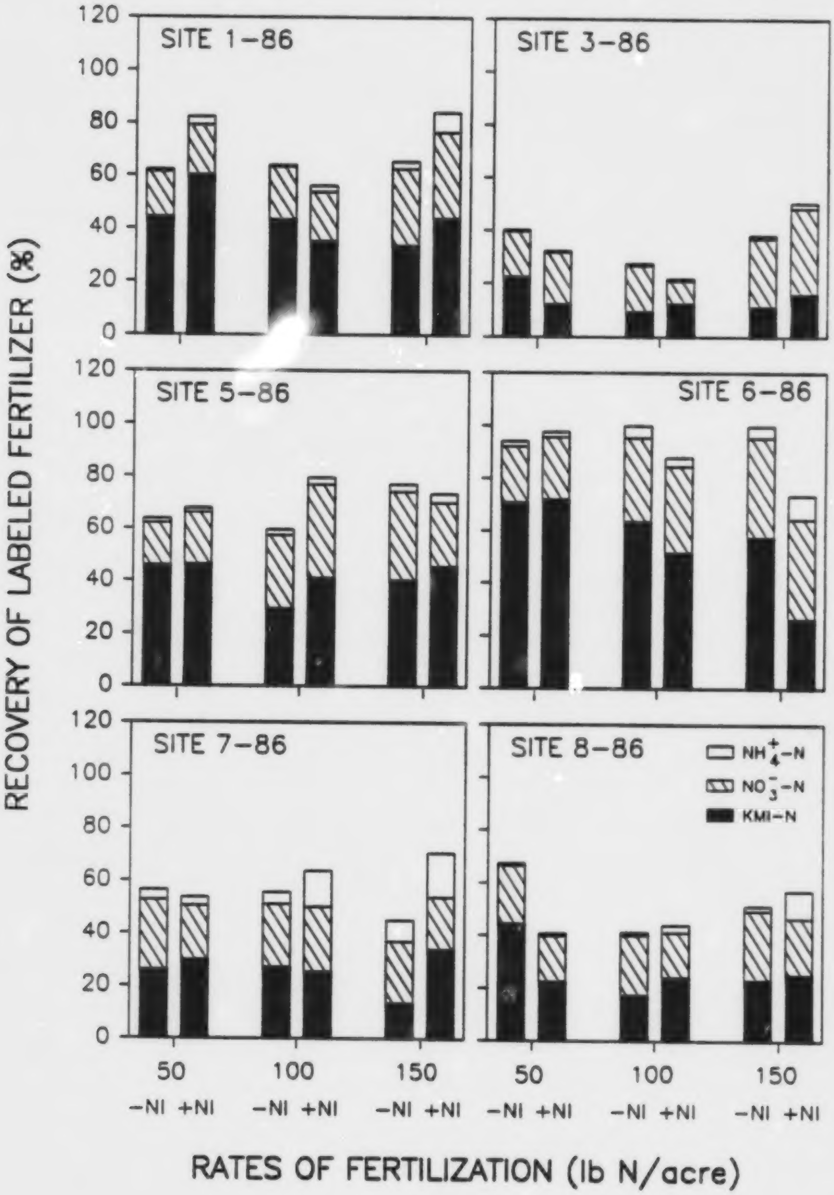


Figure 1. Recovery of labeled N in the surface 2-ft layer of soils 8 weeks after 1986 applications.

fertilizer N.

Fig. 2 shows yields of corn grain at all site-years as affected by N rate and nitrapyrin. Analysis of these data indicate that statistically significant ($P < 0.05$) yield responses to N occurred at all sites except site 5-85. However, nitrapyrin significantly increased yields only at two of the 72 rate-site-years. Mean yields were 126 and 122 bu/acre with and without nitrapyrin applied with 50 lb N/acre, 145 and 146 bu/acre with and without nitrapyrin applied with 100 lb N/acre, and 150 and 154 bu/acre with and without nitrapyrin applied with 150 lb N/acre. The increases in mean yields with increases in rates of N application indicate that lack of statistically significant yield increases due to nitrapyrin cannot be attributed to excessive amounts of available N.

Although the differences in mean yields at the lowest rate of N fertilization allows speculation that the effects of nitrapyrin may have been significant if this study had greater experimental sensitivity, such speculation has no practical significance because application of additional N would be much more profitable than the addition of nitrapyrin. Because absolute means are lower with nitrapyrin than without nitrapyrin at the highest rate of fertilization, it is more likely that greater experimental sensitivity would have shown statistically significant yield decreases rather than increases at this rate of fertilization. The possibility of yield decreases at 150 lb N/acre deserves notice because this rate is the nearest to those usually used in production agriculture, because yield decreases have been observed elsewhere with spring-applied fertilizer (Blackmer and Sanchez, 1988; Hoeft, 1984), and because any yield decrease due to nitrapyrin has economic significance to corn producers.

Rate of N application and nitrapyrin had a statistically significant effect on N concentration in the ear leaf at silking when all sites are considered (Table 3). When sites are considered individually, rate of N application had a significant effect on leaf N concentration at 17 of the 18 site-years and nitrapyrin had a significant effect at four of the 18 site-years. Nitrapyrin had a significant effect on leaf N concentration at only six of the 72 rate-site-years (Fig. 3). These observations indicate that nitrapyrin had relatively little effect on the availability of N (fertilizer-derived plus soil-derived N) in the soil at silking.

Rate of N application had a significant effect on the percentage nitrogen derived from fertilizer (PNDFF) in the ear leaf at silking of the first crop after application of labeled N (Table 4). It should be noted that ^{15}N-labeled fertilizers were applied only to selected site-years and, therefore, data from fewer site-years are presented in Table 4 than in Fig. 3. Nitrapyrin had no statistically significant effect on PNDFF in leaves, whether data from all sites were analyzed individually (data not shown) or combined. These observations indicate that nitrapyrin had no detectable effect on the availability of labeled N in the soil at silking.

Concentrations of N in grain significantly increased with addition of N fertilizer at all sites except at site 8-87 (Fig. 4). Nitrapyrin had no significant effect on N concentration in grain when data from all sites are combined. When analyzed individually, nitrapyrin had a significant effect at only two of the

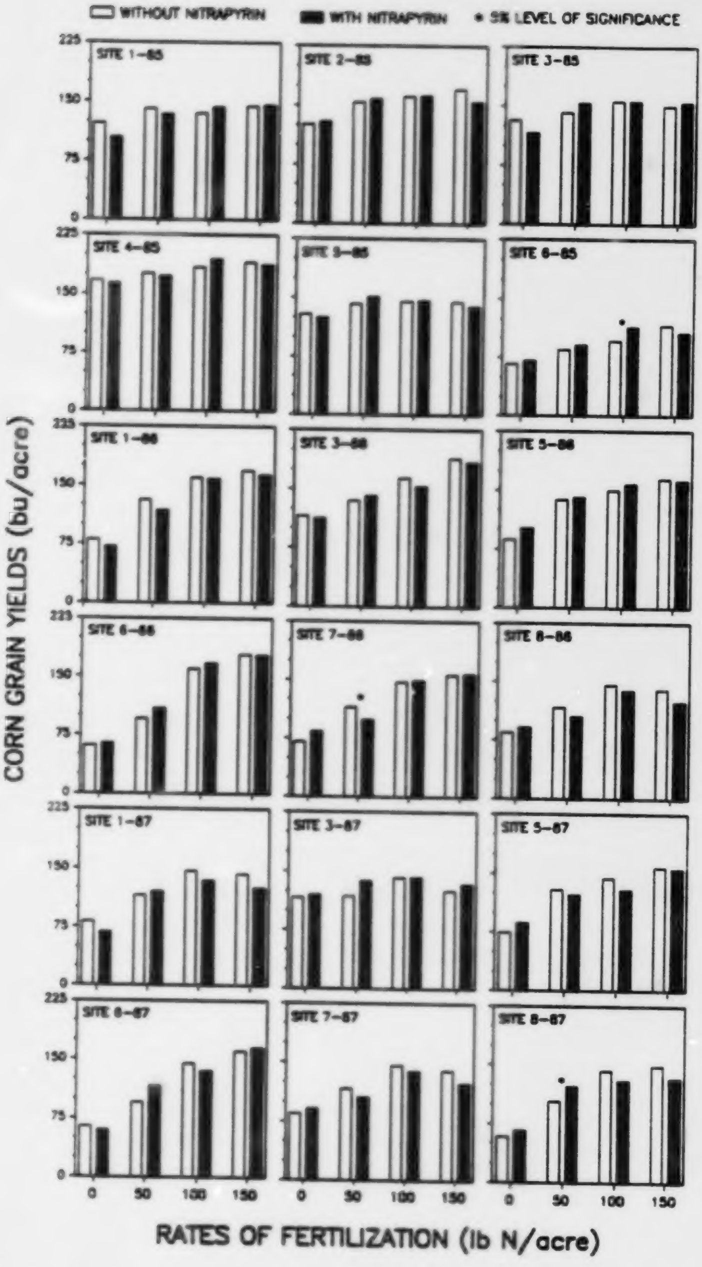


Figure 2. Corn grain yields at all site-years as affected by N rate and nitrapyrin. Asterisks indicate significant ($P < 0.05$) differences due to nitrapyrin.

Table 3. Mean N concentration in ear leaf at silking for all sites-years as affected by N rate and nitrification inhibitor (NI).

N Rate	NI	N Concentration
lb/acre		%
0	-	1.62
0	+	1.61
50	-	1.87
50	+	1.93
100	-	2.06
100	+	2.16
150	-	2.22
150	+	2.28
Statistical data:		
N Rate		0.01
NI		0.08
N Rate * NI		NS[†]
CV (%)		13.2

[†] NS indicates a probability level >0.10.

18 site-years and at only two of the 72 rate-site-years. These observations indicate that nitrapyrin had relatively little effect on the availability of N (fertilizer-derived plus soil-derived N) in the soil during the grain-filling period.

For plots treated with labeled N, PNDFF in grain of the first crop significantly increased with increase in amount of labeled N applied (Table 5). Nitrapyrin had no significant effect on PNDFF in grain, whether site-years are analyzed individually (data not shown) or combined. Percentage recovery of labeled N in grain of the first crop increased with amounts of N applied (Fig. 5). This increase in percentage recovery should be expected because an addition of labeled N dilutes the pool of available soil-derived N and because this dilution results in uptake of N having a higher percentage of labeled N. However, nitrapyrin had no significant effect on percentage of labeled N recovered in grain of the first crop when data for all site-years were combined. When data from site-years were analyzed individually, nitrapyrin had no significant effect on recovery of labeled N in grain at 22 of the 24 rate-site-

Table 4. Mean PNDFF found in ear leaf at silking of first and second crop as affected by N rate and nitrification inhibitor (NI).

N rate	NI	First crop	Second crop
lb/acre		—— PNDFF	——
50	-	13.9	1.8
50	+	13.3	1.7
100	-	23.5	2.3
100	+	23.8	2.1
150	-	34.2	3.3
150	+	32.8	3.1
Statistical data:			
N Rate		0.01	0.01
NI		NS[†]	NS
N Rate * NI		NS	NS
CV (%)		19.8	42.1

[†] NS indicates a probability level >0.10.

years. It decreased recovery at the other two rate-site-years. These observations indicate that nitrapyrin did not increase the availability of labeled N in the soil during the grain-filling period.

The percentage recovery of labeled N in stover of the first crop increased with amounts of N applied (Table 6). Nitrapyrin significantly increased the recovery of labeled N in the stover of the first crop after application of this N. This effect was significant only at the highest rate of fertilization. This evidence that nitrapyrin increased the availability of N late in the season is credible because stover has a propensity for luxury uptake of N and the concentration of N in stover is a sensitive indicator of N status at high rates of fertilization (Binford et al., 1989). However, accumulation of N in stover provides no environmental or economic benefits during grain production because the stover remains in the field.

Fig. 6 shows percentage recovery of labeled fertilizer N in the soil approximately 14 months after application of this N. This time of sampling is

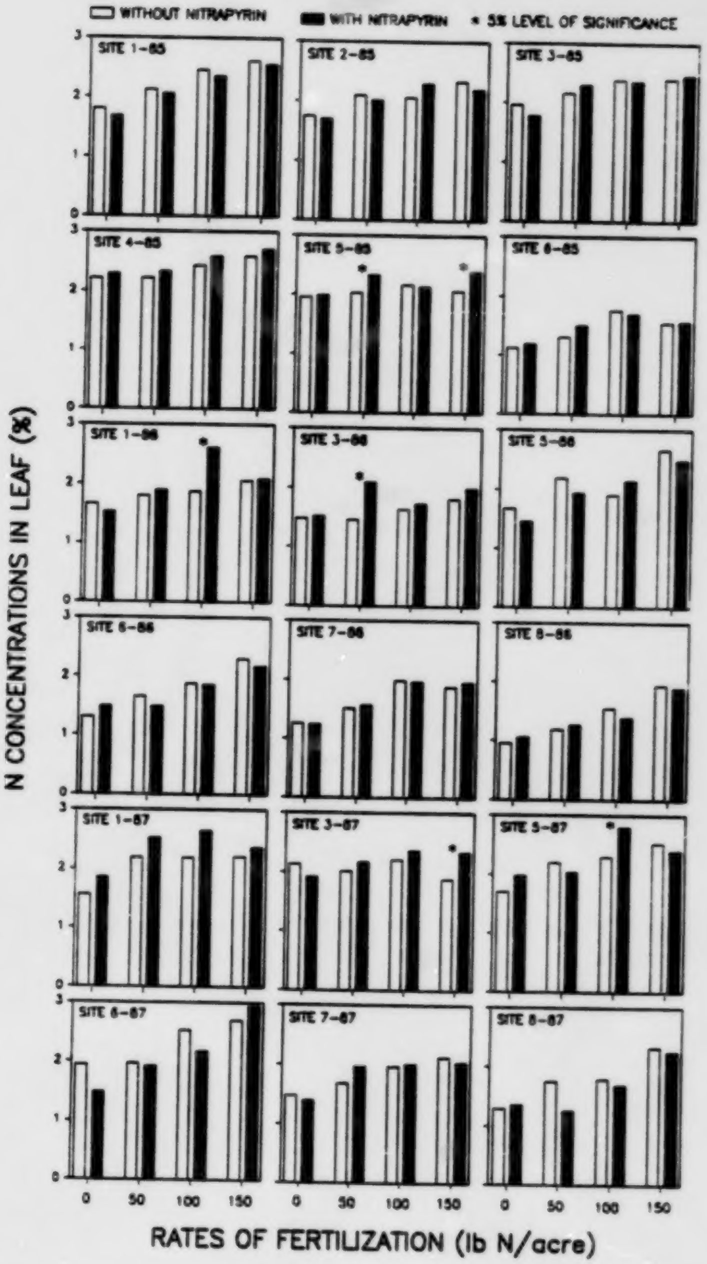


Figure 3. Concentrations of N in ear leaf at silking as affected by N rate and nitrapyrin. Asterisks indicate significant ($P < 0.05$) differences due to nitrapyrin.

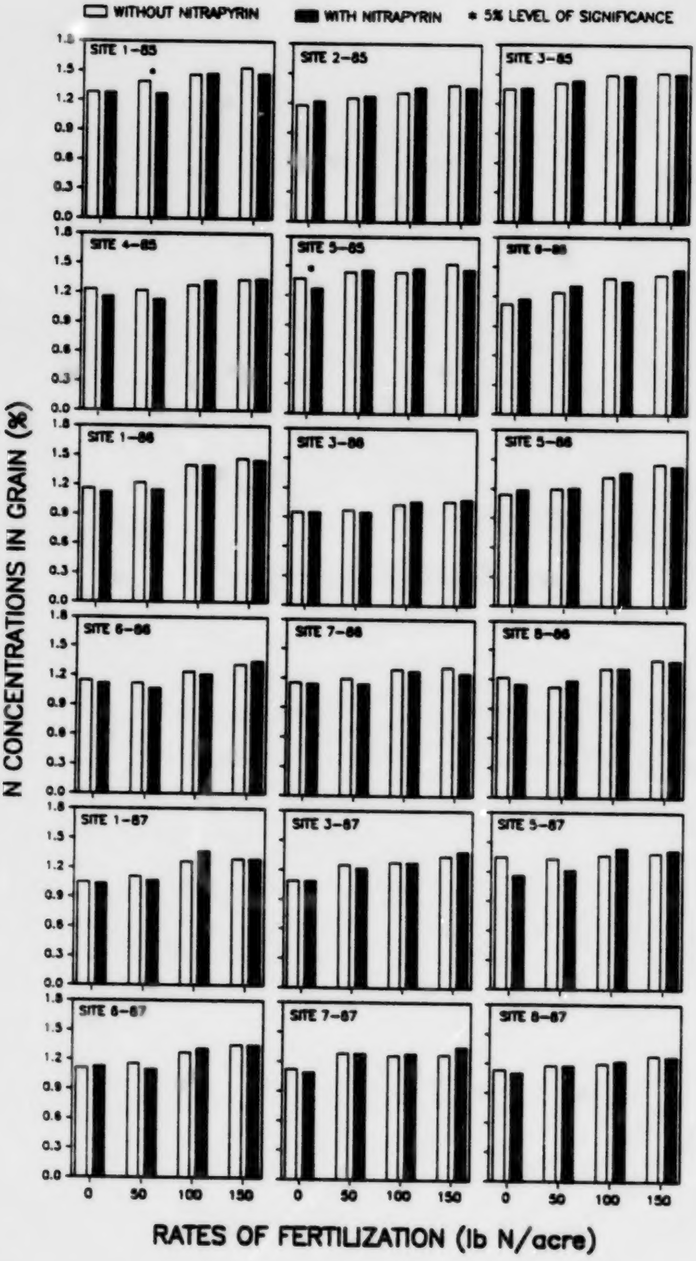


Figure 4. Concentrations of N in grain as affected by N rate and nitrapyrin. Asterisks indicate significant ($P < 0.05$) differences due to nitrapyrin.

Table 5. Mean PNDFF found in grain of first and second crop as affected by N rate and nitrification inhibitor (NI).

N rate	NI	First crop	Second crop
lb/acre		——— PNDFF ———	
50	-	11.5	1.3
50	+	10.2	1.5
100	-	19.6	2.2
100	+	19.0	2.2
150	-	26.3	3.1
150	+	28.5	3.3
Statistical data:			
N Rate		0.01	0.01
NI		NS[†]	NS
N Rate * NI		NS	NS
CV (%)		25.7	40.1

[†] NS indicates a probability level >0.10.

significant because it shows the amounts of labeled N available when the second crop after fertilization starts rapid growth and uptake of N. Data presented showed that only small amounts of this N were present as nitrate or exchangeable ammonium. Substantial amounts (mean of 30%) of labeled N were recovered in the KMI fraction. The percentage of labeled N recovered in the KMI fraction 14 months after application was slightly higher than the percentage of anhydrous ammonia-derived N found (mean of 17%) in this fraction by Sanchez and Blackmer (1988) 1 year after application. These observations support the conclusions of others (Allen et al., 1973; Legg et al., 1971; Olson, 1980; Power and Legg, 1984) that most of the fertilizer N that remains in the soil after the first cropping season is in the organic fraction.

Further evidence for relatively little carry-over of labeled N was provided by the PNDFF in ear leaves (Table 4) and grain (Table 5) in the second crop after fertilization as well as by percentage recovery of labeled N in grain (Fig. 5) and stover (Table 6) in this crop. Analyses of variance indicate that N rate had a significant effect on the amount carried over in each of these plant fractions. Nitrapyrin, however, did not have a significant effect on the amount

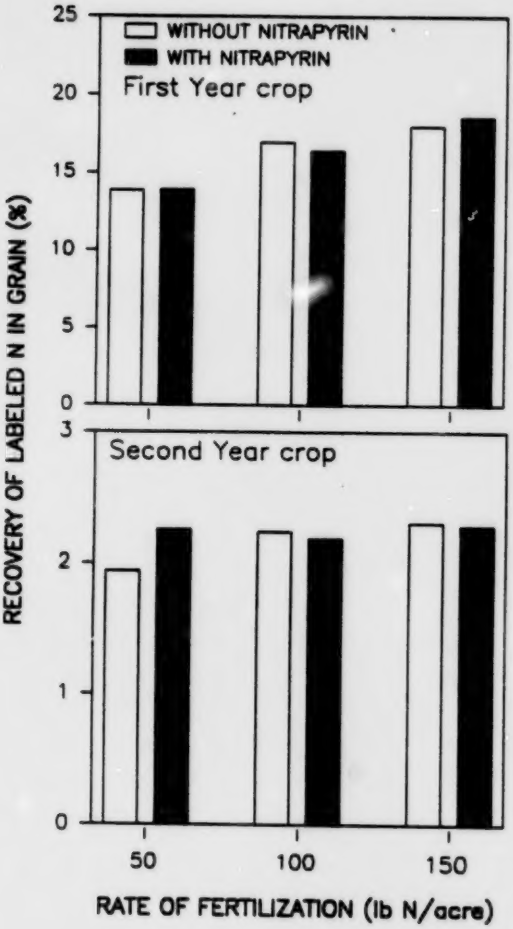


Figure 5. Percentage recovery of labeled N as affected by N rate and nitrapyrin in the first crop and second crop after application of labeled fertilizers (means of all sites).

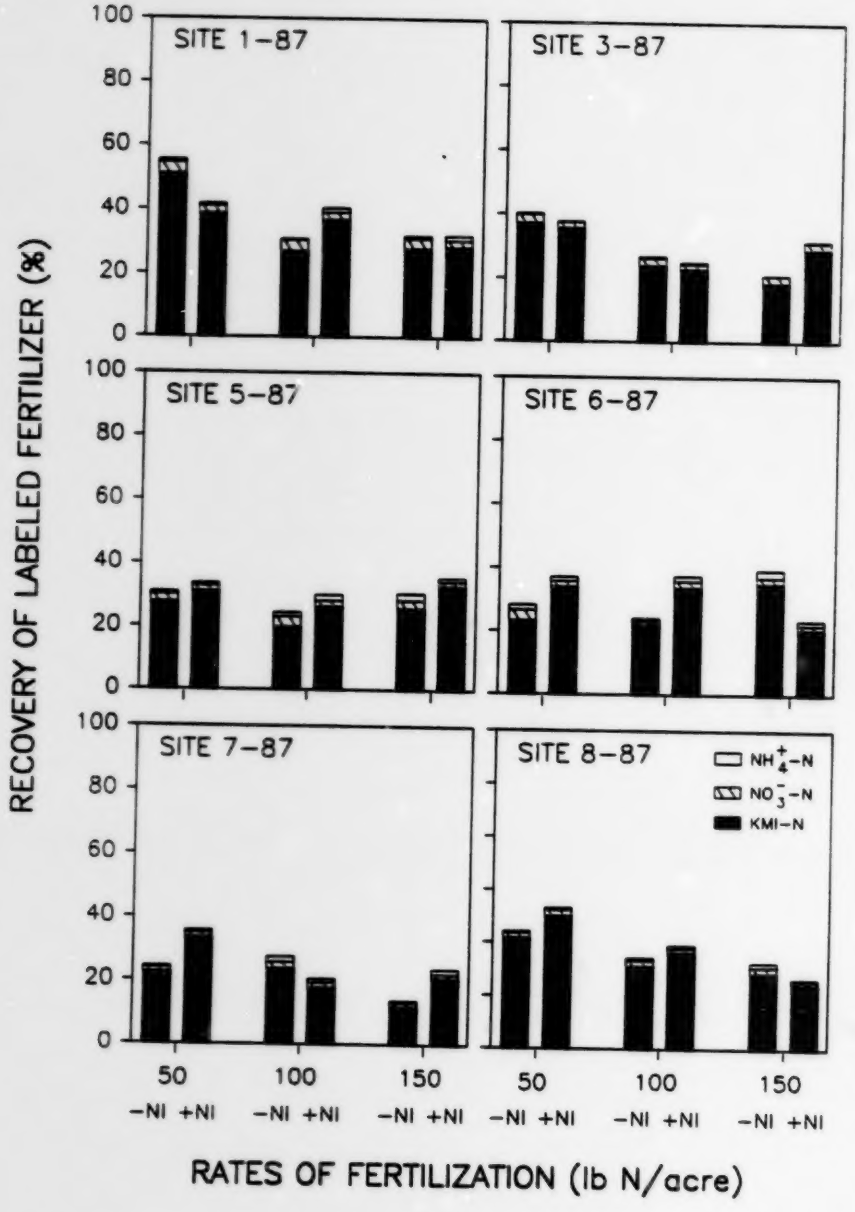


Figure 6. Recovery of labeled N in the surface 2-ft layer of soils 14 months after 1986 applications.

Table 6. Mean percent recovery of labeled N in stover of first and second crop as affected by N rate and nitrification inhibitor (NI).

N rate	NI	First crop	Second crop
lb/acre		-------- PNDFF	--------
50	-	4.9	0.9
50	+	5.5	0.8
100	-	5.7	0.8
100	+	5.6	0.9
150	-	6.1	1.0
150	+	9.1	1.2
Statistical data:			
N Rate		0.01	0.01
NI		0.02	NS[†]
N Rate * NI		0.04	NS
CV (%)		41.3	31.9
LSD[‡]		1.7	–

[†] NS indicates a probability level >0.10.

[‡] LSD values apply only to comparisons of means for treatments with and without NI. An LSD value is shown only if the effect of N Rate * NI was significant at the 10% level or less.

carried over in any of these fractions. The small recoveries of labeled N in the second crop after fertilization are consistent with the observations made by Sanchez and Blackmer (1988). They are not consistent, however, with the idea (Ashworth, 1986) that nitrification inhibitors should be regarded as tools for decreasing the N fertilizer requirement of the second crop after fertilization.

Overall, use of nitrapyrin was not cost-effective in this study. It did not increase yields, and it did not increase amounts of fertilizer N recovered in soil or plant.

This work was supported in part by the Fertilizer Trust Account of the Iowa Department of Agriculture and Land Stewardship, in part by Dow Chemical U.S.A., and in part by the

Integrated Farm Management Demonstration Program of the Agricultural Energy Management Fund, State of Iowa, through the Iowa Department of Agriculture and Land Stewardship.

LITERATURE CITED

Allen, A. L., F. J. Stevenson, and L. T. Kurtz. 1973. Chemical distribution of residual nitrogen fertilizer in soil as revealed by nitrogen-15 studies. J. Environ. Qual. 2:120-124.

Ashworth, J. 1986. Comments on "Nitrification inhibition by nitrapyrin and volatile sulfur compounds." Soil Sci. Soc. Am. J. 50:268-269.

Binford, G. D., A. M. Blackmer, and N. M. El-Hout. 1989. A tissue test for excess nitrogen during corn production. Agron. J. (in press).

Blackmer, A. M. 1986. Potential yield response of corn to treatments that conserve fertilizer nitrogen in soils. Agron. J. 78:571-575.

Blackmer, A. M., and C. A. Sanchez. 1988. Response of corn to nitrogen-15-labeled anhydrous ammonia with and without nitrapyrin in Iowa. Agron. J. 80:95-102.

Bremner, J. M., and C. S. Mulvaney. 1982. Nitrogen-total. In A. L. Page et al. (ed.) Methods of soil analysis, Part 2. Agronomy 9:595-624. ASA, Madison, WI.

Briggs, G. G. 1975. The behaviour of the nitrification inhibitor "N-Serve" in broadcast and incorporated application to soil. J. Sci. Fd. Agric. 26:1083-1092.

Cerrato, M. E., A. M. Blackmer, and D. L. Priebe. 1985. Movement of ^{15}N-3labeled nitrate in the rooting zone of Iowa soils. p. 23. In Agronomy Abstracts. ASA, Madison, WI.

Frye, W. W., R. L. Blevens, L.W. Murdock, K. L. Wells, and J. H. Ellis. 1981. Effectiveness of nitrapyrin with surface applied fertilizer nitrogen in no-tillage corn. Agron J. 73:287-289.

Goring, C. A. I. 1962. Control of nitrification by 2-chloro-6-(trichloromethyl) pyridine. Soil Sci. 93:211-218.

Hanson, R. G., S. R. Maledy, and C. E. Jentes. 1987. Effects of anhydrous ammonia with and without nitrapyrin applied fall and spring on corn yield. Comm. Soil Sci. Plant Anal. 18:387-403.

Hauck, R. D. 1983. Agronomic and technological approaches to minimizing gaseous nitrogen losses from cropland. p. 285-312. In J. R. Freney, and J. R. Simpson (ed.) Gaseous loss of nitrogen from soil-plant systems. Martinus Nijhoff Publ., Boston, MA.

Hergert, G. W., and R. A. Wiese. 1980. Performance of nitrification inhibitors in the Midwest (West). p. 89-105. In J. J. Meisinger et al. (ed.) Nitrification inhibitors-potentials and limitations. Spec. Pub. 38. ASA, Madison, WI.

Hoeft, R. G. 1984. Current status of nitrification inhibitors in U.S. agriculture. p. 563-569. In R. D. Hauck (ed.) Nitrogen in crop production. ASA. Madison, WI.

Huber, D. M., H. L. Warren, D. W. Nelson, and C. T. Tsai. 1977. Nitrification inhibitors-New tools for food production. Bioscience 27:523-529.

Juma, N. G., and E. A. Paul. 1983. Effect of a nitrification inhibitor on N immobilization and release of ^{15}N from nonexchangeable ammonium and microbial biomass. Can J. Soil Sci. 63:167-175.

Keeney, D. R. 1980. Nitrogen management for maximum efficiency and minimum pollution. In F. J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agronomy 22:605-649.

Legg, J. O., F. W. Chichester, G. Stanford, and W. H. DeMar. 1971. Incorporation of ^{15}N-tagged mineral nitrogen into stable forms of soil organic nitrogen. Soil Sci. Soc. Am. Proc. 35:273-276.

Meisinger, J. J., G. W. Randall, and M. L. Vitosh (ed.) 1980. Nitrification inhibitors-potentials and limitations. Spec. Publ. 38. ASA, Madison, WI.

National Oceanic and Atmospheric Administration. 1985. Climatological data. Iowa. Vol. 96. NOAA, Environmental Data and Information Service, National Climatic Center, Asheville, NC.

National Oceanic and Atmospheric Administration. 1986. Climatological data. Iowa. Vol. 97. NOAA, Environmental Data and Information Service, National Climatic Center, Asheville, NC.

National Oceanic and Atmospheric Administration. 1987. Climatological data. Iowa. Vol. 98. NOAA, Environmental Data and Information Service, National Climatic Center, Asheville, NC.

Olson, R. V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. Soil Sci. Soc. Am. J. 44:514-517.

Owens, L. B. 1981. Effects of nitrapyrin on nitrate movement in soil columns. J. Environ. Qual. 10:308-310.

Owens, L. B. 1987. Nitrate leaching losses from monolith lysimeters as influenced by nitrapyrin. J. Environ. Qual. 16:34-38.

Parr, J. F. 1973. Chemical and biochemical considerations for maximizing the efficiency of fertilizer nitrogen. J. Environ. Qual. 2:75-84.

Power, J. F., and J. O. Legg. 1984. Nitrogen-15 recovery for five years after application of ammonium nitrate to crested wheatgrass. Soil Sci. Soc. Am. J. 48:322-326.

Priebe, D. L. 1988. Preferential leaching of surface-applied nitrogen fertilizers in Iowa soils. Ph. D. Thesis Iowa State University, Ames, IA.

Sanchez, C. A. 1986. ^{15}N-tracer studies of the transformations, movement, and recovery of anhydrous ammonia-derived N in the rooting zone of corn. Ph. D. Thesis. Iowa State University, Ames, IA.

Sanchez, C. A., and A. M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. Agror J. 80:102-108.

Spector, P. C., J. H. Goodnight, J. P. Sall, and W. S. Sarle. 1985. The GLM procedure. p. 433-506. In SAS User's Guide: Statistics, 1985 ed. SAS Institute Inc., Cary, NC.

FACTORS AFFECTING THE CARRYOVER AND BIOAVALABILITY OF TRIALLATE AND TRIFLURALIN ON MANITOBA SOILS

G.A.ROSS[1], G.R.B.WEBSTER[1], and C.F.SHAYKEWICH

Department of Soil Science
[1] Pesticide Research Laboratory
University of Manitoba
Winnipeg, MB R3T 2N2

1. INTRODUCTION

Herbicide use on the Canadian prairies has become an important factor in achieving higher crop yields. This has lead to a general increase in the amounts of herbicides applied to the soil. The soil constitutes a reservoir for herbicide residues, and many factors affect their behaviour in the soil. Identifying key soil and environmental factors in Manitoba and understanding their role is expected to help in the prediction of herbicide carryover and persistence in soils. Therefore, an understanding of how herbicides interact with soil is essential to enable the safe, effective and efficient use of herbicides.

A herbicide must persist long enough to provide a level or duration of weed control that is acceptable but not long enough to put limitations on the viability of subsequent crops (Walker, 1974). Carryover and persistence of herbicide residues in agricultural soils is an important phenomenon. Persistence of herbicides may represent an economic benefit to the farmer by providing two consecutive seasons of weed control. However, interference with crop rotation practices and damage to grain crops in subsequent years following application may occur if the second year crop is susceptible to the residual herbicide. This may result in a serious economic problem.

Trifluralin and triallate are among the more commonly used herbicides in Western Canada (Smith and Muir, 1984). Trifluralin, as a pre-emergent herbicide in wheat and barley and as preplant in canola, is used to control green and yellow foxtail. Triallate, as a preplant or postplant incorporated herbicide in wheat or preplant incorporated herbicide in canola, is used for the control of wild oats. Trifluralin and triallate applied to agricultural soils have the potential to persist in the soil and residues may carryover from one growing season to the next. Smith (1970) observed that 15-20% of the triallate applied at 2.8 kg ha^{-1} persisted in a Regina heavy clay at the end of a five month growing season. Walker (1978) observed in field trials over two years between 55 and 70% of the amounts of trifluralin applied remained 4-5 months after spray application.

It has been well demonstrated that the amount of moisture present in the soil will affect the dissipation of these herbicides (Smith 1971, Walker 1974, and Smith and Hayden 1982). Volatilization rate is increased by increased moisture content in the soil, and is the dominant process for dissipation of triallate and trifluralin throughout the growing season until freeze-up (Grover et al, 1988).

Studies were initiated to:

(1) conduct field trials to measure the amount of carryover and persistence of two common soil applied herbicides on three different soil types

(2) evaluate factors responsible for this carryover and persistence

2. MATERIAL AND METHODS

Three southwestern Manitoba soils were selected on the basis of texture (Table 1). Soil texture analyses were determined using the pipet method (Kilmer and Alexander, 1949) and organic carbons were determined using the method of Yeomans and Bremner (1988).
Soil samples were removed from storage at -32°C and thawed. One sample was immediately taken for soil moisture test. The remainder of the sample was air dried and ground to a fine powder. Fifteen gram subsamples were extracted with an acetonitrile:water:acetic acid (80:20:2.5) solution with partitioning into hexane (Grover et al, 1988). Hexane was dried with two grams of anhydrous sodium sulphate, then injected directly into a Varian Series 2400 gas chromatograph equipped with a tritium foil electron capture detector and a 5% OV-101 packed column on Chromosorb W HP 80-100 mesh. The recovery of samples with known amounts of trifluralin and triallate in storage with field samples was greater than 90%; therefore, no correction factor was used. Precipitation during the April-October period of each study year is illustrated in Table 2.

a) Field Trial

Trifluralin applied as Treflan EC (545 g ai L^{-1}) was spring applied (preplant) in 1986 and 1988 to all sites at the recommended rate of 2.00 L ha^{-1} (Table 3). Following application, the trifluralin was immediately incorporated to a depth of five centimeters using a 3 point hitch tandem disc followed by another discing at right angle to the first. Triallate applied as Avadex BW (400 g ai L^{-1}) was spring applied (pre-emergent) in 1987 to all sites at the recommended rate of 3.5 L ha^{-1} (Table 3). Following application, the triallate was immediately incorporated to a depth of five centimeters by a harrowing followed by another harrowing at right angles to the first. The experimental design consisted of four replicate plots. For the Pembina CL site, plots were 3.2 m wide by 16.8 m long. For the Ryerson FSL and the Willowcrest FS sites, plots were 5.6 m wide by 16.8 m long. Soil sampling to a depth of 5 cm was conducted on each site prior to spraying, at specific times during the growing season and prior to freeze-up (Table 4). Three samples were taken per replication, combined, placed in plastic bags, and stored at -32°C until analysis. Two duplicate fifteen gram samples were used for analysis. All sites were fertilized as recommended following soil test results from the Manitoba Provincial Soil Testing Laboratory.

b) Petri Dish Trial

Soils with varying textures (Table 1) and organic matter contents of 4.5% (Pembina CL), 2.5% (Ryerson FSL), and 3.9% (Willowcrest FS) were treated with five rates of triallate and five rates of trifluralin. Eight pregerminated Dumont oat seeds were placed in a petri dish with fifty grams of untreated soil or fifty grams of treated soil at each rate. Each rate was replicated five times. The petri dishes were watered to field capacity and incubated at 22°C for five days. The longest root length was measured as an indication of the availability of the herbicide to the growing seedling.

c) Growth Chamber Trial

Soil, as used in the petri dish trial, was treated with four rates of triallate and four rates of trifluralin. Trials with untreated soil (controls) as well as trials with a 4 cm layer of the treated soil placed on top of 8 cm of untreated soil were grown for 56 days. Each rate was replicated three times. Katepwa wheat was seeded 2 cm into the treated layer. Soil was watered to field capacity. Soil fertility for three soils was low. Supplemental fertilizer was added to each soil (150 ppm N as NH_4NO_3, 100 ppm K as K_2SO_4, and 20 ppm P as H_3PO_4). Dry matter yields were taken 28 days after germination and 56 days after germination. The day time and night time temperature in the growth chamber were 24°C and 16°C respectively. A 16h photoperiod was used. The relative humidity was 70% in the day time and 90% at night.

3. RESULTS AND DISCUSSION

a) Field Trials

Table 5 shows the persistence of triallate. The Pembina CL soil retained the highest amount of triallate (1.72 ppm) one week after spray application, while the Willowcrest FS retained more triallate (0.98 ppm) than the Ryerson FSL (0.60 ppm). The triallate concentration in the soil initially decreases rapidly from sampling time T_0 to sampling time T_1 followed by a more gradual dissipation of triallate over the remainder of the growing season. There is no significant loss of triallate over the winter months. However, all sites show a decrease in amount of triallate that is extractable. Triallate concentration did not significantly decrease in 1988 on the Pembina CL soil or the Willowcrest FS soil. The carryover residues into the spring of 1988 showed that the Pembina CL soil retained a higher concentration of triallate than the Ryerson FSL or the Willowcrest FS even though carryover per cents were similar (Table 7). Table 6 shows the persistence of trifluralin. Carryover residues of trifluralin were significantly higher on the Pembina CL soil (0.54 ppm) than on the Ryerson FSL (0.22 ppm) and the Willowcrest FS (0.14 ppm). The carryover residues into the spring of 1989 showed that the Pembina CL soil retained a higher concentration of trifluralin than the Willowcrest FS even though the Pembina CL soil and the Willowcrest FS carried-over 52% and 65% of the initial spray concentration respectively (Table 8). There was no significant loss of trifluralin over the winter months. After spring application of trifluralin in 1988, more trifluralin was retained by the Pembina CL soil while similar amounts were retained by the Ryerson FSL and the Willowcrest FS. Higher carryover residues combined with more retained spray residues in 1988 increased the amount of extractable trifluralin residues in the Pembina CL soil as compared to the Ryerson FSL and the Willowcrest FS. The loss of triallate and trifluralin in the year of spraying followed the three phase dissipation discussed by Grover et al (1988). Table 5 shows the first year and the second year triallate carryover residues. Table 6 shows the trifluralin carryover residues.

b) Petri Dish Trial

The triallate appeared to have no effect on root growth of the oat seedling up to a level of 2.0 ppm. Trifluralin had a more substantial effect on the root growth of the oat seedlings by reducing growth (Fig.1). Olson and McKercher (1985) observed root damage at 0.4 ppm for various cultivars of wheat. The Pembina CL and the Willowcrest FL (% organic matter content = 4.5 and 3.9 respectively) showed an increase in affect to root growth as trifluralin concentration increased. At a level of 0.68 ppm a significant decrease in root length occurred for the Pembina CL and the

Willowcrest FS. However, the Ryerson FSL (2.5 % organic matter content) showed a significant increase in activity of the trifluralin at a level of 0.35 ppm.

c) Growth Chamber Trial

The triallate at rates of 0.40 to 1.80 ppm had no effect on the growth of Katepwa wheat. The trifluralin at rates of 1.40 ppm greatly reduced the dry matter yield of the wheat at sampling day 28 after germination and the plants never recovered from the initial stunting when testing was done 56 days after germination (Table 9). The growth of wheat in the Willowcrest FS soil appeared to be least affected by the trifluralin rates. This may have been due to more availability of nutrients (especially nitrogen) to the plants because of the coarser texture of the soil. Nutrients which are more available to the affected roots may allow them better growth to penetrate the treated layer and thus allow for better visible growth of the wheat. A rate of 1.40 ppm was required to affect wheat growth while a rate of 0.70 ppm did not affect wheat growth.

4. CONCLUSION

1. The Pembina CL soil retained more triallate and trifluralin than either the Ryerson FSL or the Willowcrest FS. However, the Ryerson FSL and the Willowcrest FS retained similar amounts of the two herbicides. Since the organic matter content is significantly higher in the Pembina CL soil, the per cent organic matter appears to be a major factor in retaining triallate and trifluralin.

2. Persistence of triallate and trifluralin follow a three-phase dissipation similar to that described by Grover et al (1988). The rate of dissipation is similar on the three sites; however, the amount of herbicide retained by the Pembina CL is significantly higher initially than the Ryerson FSL or the Willowcrest FS.

3. The triallate residue had no effect on root growth. The trifluralin had a greater effect on the low organic matter soils much sooner than on a higher organic matter soil, regardless of clay content. The rates of trifluralin carryover on all soils types studied had the ability to reduce the growth of the oat seedlings and therefore had the potential to damage subsequent susceptible crops.

4. Triallate residues had no effect on wheat growth. Trifluralin at 1.40 ppm had a significant effect on wheat growth. Fertilizer availability appeared to mask some effect of the trifluralin injury.

5. The dry summer of 1988 appeared to increase the persistence of triallate and trifluralin.

6. The rates of herbicide breakdown for all three soils are essentially the same. Therefore, the more herbicide retained initially, the greater will be the carryover and persistence of the herbicide. Triallate carryover rates appear not to be a problem. Trifluralin carryover residues may be a problem if conditions are present to cause poor emergence of the crop.

5. REFERENCES

Grover, R., A.E. Smith, S.R. Shewchuk, A.J. Cessna, and J.H. Hunter. 1988. Fate of trifluralin and triallate applied as a mixture to a wheat field. J. Environ. Qual. 17:543-550.

Kilmer, V.J. and L.T. Alexander. 1949. Methods of making mechanical analysis of soils. Soil Sci. 68:15-24.

Olson, B.M. and R.B. McKercher. 1985. Wheat and triticale root development as affected by trifluralin. Can. J. Plant Sci. 65:723-729.

Smith, A.E. 1970. Degradation, adsorption, and volatility of diallate and triallate in prairie soils. Weed Res. 10:331-339.

Smith, A.E. 1971. Dissappearance of triallate from field soils. Weed Sci. 19:536-537.

Smith, A.E. and B.J Hayden. 1982. Carry-over of Dinitramine, triallate, and trifluralin to the following spring in soils treated at different times during the fall. Bull. Environm. Toxicol. 29, 483-486.

Smith, A.E. and D.C.G. Muir. 1984. Determination of extractable and nonextractable radioactivity from small field plots 45 and 95 weeks after treatment with [^{14}C]dicamba, (2,4-dichloro[^{14}C]phenoxy)acetic acid, [^{14}C]triallate, and [^{14}C]trifluralin. J. Agric. Food Chem. 32:588-593.

Walker, A. 1974. A simulation model for prediction of herbicide persistence. J. Environ. Quality, 3:396-401.

Walker, A. 1978. Simulation of the persistence of eight soil-applied herbicides. Weed Res. 18:305-313.

Yeomans, J.C. and J.M. Bremner. 1988. A rapid and precise method for routine determination of organic carbon in soil. Commun. in Soil Sci. Plant Anal., 19(13), 1467-1476.

Table 1: Composition and physical characteristics of field soils

Soil Type	% Sand	% Silt	% Clay	% OM[1]
Pembina CL	27	43	30	4.5
Ryerson FSL	56	27	17	3.0
Willowcrest FS	90	1	9	3.2

[1] % Organic Matter = % Organic Carbon * 1.7

Table 2: Precipitation (mm) from April to October

Site	1987	1988	30 Year Ave
Pembina CL	391.3	222.3	432.3
Ryerson FSL	341.6	305.6	389.7
Willowcrest FS	385.5	237.5	371.3

Table 3: Spray dates

	1986	1987	1988
Pembina CL	May 21	May 15	May 18
Ryerson FSL	May 20	May 15	May 5
Willowcrest FS	May 13	May 15	May 12

Table 4: Sampling dates

Sampling Time		1987	1988	1989
T_{-1}	Willowcrest FS	May 10	May 4	April 27
	Pembina CL	May 11	May 5	April 27
	Ryerson FSL	May 12	May 4	-
T_0	Willowcrest FS	May 26	May 27	
	Pembina CL	May 27	June 3	
	Ryerson FSL	May 28	May 25	
T_1	Willowcrest FS	July 23	Aug. 2	
	Pembina CL	July 23	July 29	
	Ryerson FSL	July 24	July 28	
T_2	Willowcrest FS	Oct. 26	Oct. 29	
	Pembina CL	Oct. 26	Oct. 28	
	Ryerson FSL	Oct. 27	-	

Table 5: Mean of triallate residues in the top 5 cm soil layer versus time in days over 2 year period following application

Sampling Time	Site		
	Pembina CL	Ryerson FSL	Willowcrest FS
1987			
T_0	1.72 a	0.60 c	0.98 b
T_1	1.16 a	0.36 b	0.56 b
T_2	0.75 a	0.23 b	0.44 b
1988			
T_{-1}	0.52 ab	0.16 c	0.30 bc
T_0	0.61 a	0.16 b	0.16 b
T_1	0.50 a	0.08 b	0.21 b
T_2	0.45 a	-	0.10 b
1989			
T_{-1}	0.41 a	-	0.19 b

Values in a row followed by the same letter are not significantly different at P=.05 using a Duncan's Multiple Range Test.

Table 6: Mean of trifluralin residues in the top 5 cm soil layer versus time in days over 2 year period

Sampling Time	Site		
	Pembina CL	Ryerson FSL	Willowcrest FS
1987			
T_{-1}	0.54 a	0.22 b	0.14 b
T_0	0.39 a	0.18 b	0.13 b
T_1	0.33 a	0.14 b	0.08 b
T_2	0.31 a	0.12 b	0.07 b
1988			
T_{-1}	0.29 a	0.08 b	0.06 b
T_0	1.10 a	0.50 b	0.54 b
T_1	0.86 a	0.35 c	0.52 b
T_2	0.63 a	-	0.37 b
1989			
T_{-1}	0.57 a	-	0.35 b

Values in a row followed by the same letter are not significantly different at P=.05 using a Duncan's Multiple Range Test.

Table 7: Carryover rates of triallate

Triallate	Site Pembina CL	 Ryerson FSL	 Willowcrest FS
Initial Rate	1.72	0.60	0.98
Carryover 1988	0.52	0.16	0.30
Carryover %	30	27	31
Carryover 1989	0.41		0.19
Carryover %	24		19

Table 8: Carryover rates of trifluralin

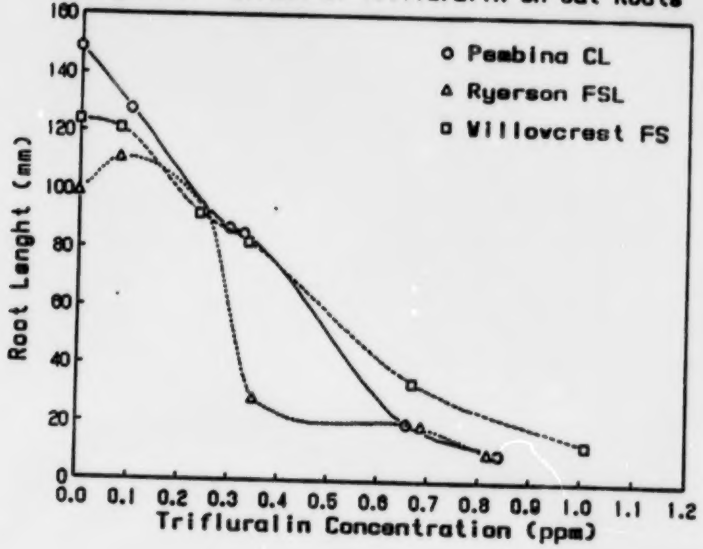
Triallate	Site Pembina CL	 Ryerson FSL	 Willowcrest FS
Carryover 1987	0.54	0.22	0.14
Carryover 1988	0.29	0.08	0.06
Carryover %	54	36	43
Initial Rate	1.10	0.50	0.54
Carryover 1989	0.57		0.35
Carryover %	52		65

Table 9: Growth chamber experiment dry matter weights using various rates of trifluralin[1]

	Site Pembina CL		Ryerson FSL		Willowcrest FS	
Trifluralin	Days After Germination					
Conc.(ppm)	28	56	28	56	28	56
0.28	0.18	4.76	0.22	6.36	0.30	7.27
0.70	0.14	5.25	0.15	6.36	0.26	7.54
1.40	0.02	1.87	0.03	1.54	0.14	7.43
1.73	0.02	0.51	0.03	0.51	0.07	2.86
Control	0.18	5.17	0.20	5.79	0.28	7.26

[1] Dry matter weights are given as a combined average of 3 plants weights.

Figure 1: Effect of Trifluralin on Oat Roots



The Effect of Chloride Fertilizer on Crop Yield

R.M. Mohr and D.N. Flaten
Department of Soil Science, Univ. of Manitoba

Introduction

In 1938 it was demonstrated that chloride was beneficial to crop growth, but it was not until 1954 that chloride was established as an essential nutrient (Beaton and Speer, 1961). The amount of chloride required for plant growth is very small relative to typical concentrations of chloride in soil and precipitation. Therefore, until recently, there was little interest in chloride as a fertilizer.

In the past decade, however, crop responses to chloride-containing fertilizers have been observed on soils where the concentration of chloride exceeds the level required strictly for plant nutrition. Many of these responses have been observed as a byproduct of research into other nutrients. For example, potassium chloride fertilizer has increased crop yields on soils high in potassium where other potassium fertilizers had no effect.

Sources of Chloride

Within the lithosphere, the chlorine content is approximately 0.05% in metamorphic and igneous rocks and 0.02% in limestones. Chlorine is usually present at trace levels in sedimentary sandstones and is generally absent in shales. However, atmospheric deposition results in sufficient supplies of Cl for plant nutrition in most areas except those far inland from sea.

Movement and Plant Uptake of Chloride

Chloride is readily mobile in soil and leaches easily. Therefore, broadcast application of Cl fertilizer is generally regarded as being as effective as seed row placement.

The critical concentrations of chloride for plant nutrition are only 2 mg/kg in soil, or 70 to 100 mg/kg in plant tissue. However, the accumulation of chloride by plants is variable, depending on the chloride concentration in the substrate. As a result, the chloride concentration in plant tissue often exceeds the so-called "critical level" for its role as a micronutrient (eg. chloride concentrations of 1000 to 10,000 mg/kg are common in wheat). Chloride is not readily mobile in plant tissue and accumulates in older leaves, causing younger leaves to show chlorotic deficiency symptoms first.

Roles of Chloride in the Soil-Plant System

Chloride plays a key role in many functions within the soil-plant system.

a) Photosynthesis and Enzyme Activation

Chloride is required specifically for a number of biochemical processes in the plant including photosystem II of photosynthesis and optimal activity of certain enzymes, including alpha amylase, asparagine synthetase and ATPase (Maas, 1986).

b) Chloride-Disease Interaction

Chloride has been shown to significantly reduce many plant diseases in a variety of common field crops. (Table 1)

Table 1. Diseases suppressed by chloride fertilizers
(modified from Fixen, 1987)

Location	Crop	Suppressed Disease
Oregon	Winter Wheat	Take-all root rot
Germany	"	"
North Dakota	"	Tanspot
Oregon	"	Stripe Rust
Oregon	"	Septoria
Great Britain	"	"
South Dakota	Spring Wheat	Leaf Rust
South Dakota	"	Tanspot
South Dakota	"	Septoria
North Dakota	"	Common Root Rot
Saskatchewan	"	"
Alberta	Barley	Common Root Rot
Alberta	"	Net Blotch
North Dakota	"	Common Root Rot
North Dakota	"	Spot Blotch
Montana	"	Fusarium Root Rot
Saskatchewan	"	Common Root Rot
North Dakota	Durum Wheat	Common Root Rot

A number of mechanisms have been suggested to explain the disease suppression effect of chloride. Chloride is an essential nutrient; therefore, plants lacking in chloride may be nutritionally predisposed to disease (Goos et al., 1987). Infection by plant pathogens may be inhibited by a decrease in water potential and an increase in turgor pressure caused by chloride accumulation (Fixen, 1987; Goos et al., 1986). Chloride in soil may enhance the activity of soil microorganisms detrimental to the growth of plant pathogens (Beaton, 1984). Chloride may also affect disease levels through its effect on nitrogen levels in the plant. Goos et al.(1987) proposed that the competitive effect between chloride and nitrate results in reduced nitrate levels in the plant thus resulting in disease suppression. Chloride also acts to inhibit nitrification in moderately acid soils causing ammonium to be taken up in place of nitrate (Christensen et al., 1986). Thus, hydrogen ions are given off at the root surface, pH declines and the occurrence of microorganisms detrimental to plant pathogens is enhanced (Smiley and Cook, 1973).

c) Chloride-Manganese Interaction

In acid soils, chloride increases the concentration of manganese in plant tissue perhaps as a result of forming a $MnCl^+$ complex in soil. This may be of special significance since it has been found that low manganese availability makes plants more susceptible to disease (Beaton et al., 1988).

d) Plant Water Relations

The chloride ion plays several roles in the control of water relationships within the plant. It is an important osmotic solute required for maintaining turgor in plant cells. In addition, it acts as a counterion for cation movement and is involved in stomatal regulation (Maas, 1986).

Benefits of Chloride Fertilization for Wheat and Barley Production

In North Dakota, potassium chloride fertilizer resulted in a consistent response in barley but not in spring wheat. The response noted in barley appears to be related to the disease suppressant activity of chloride (Goos, 1986). In South Dakota, the addition of chloride fertilizers resulted in yield increases in both barley and wheat (Fixen et al., 1986). Not all of these yield responses have been linked to a suppression of disease however. Therefore some other mechanism may be at least partially responsible (Fixen, 1987; Beaton et al., 1988). Research in Oregon has also shown a yield response to chloride fertilizers applied to cereals. Once again, the yield response was attributed to a chloride-disease interaction (Goos, 1986, Beaton et al., 1988).

Several factors which affect the probability of receiving a chloride response have been identified. Research in South Dakota indicates that a yield response is likely in soils containing less than 66 kg/ha chloride in the top 60 cm. However, North Dakota researchers have found this guideline to somewhat unreliable in the prediction of a profitable yield response to chloride fertilizers. Other factors include the type of disease, the amount of disease pressure and the species and variety of crop (Fixen, 1987).

Ongoing Chloride Research at the University of Manitoba

In 1988, a three year joint project involving the Departments of Plant Science and Soil Science at the University of Manitoba was initiated. The overall objective of this project is to determine the profitability of chloride fertilization in Manitoba. More specifically, the project will help to determine the chloride status of Manitoba soils as well as the effect of chloride fertilization on yield, disease levels, plant nutrition and grain quality of wheat and barley.

In order to fulfil these objectives, the project has been undertaken in two phases:

a) Chloride Levels in Manitoba Soils

In the initial phase of the experiment conducted in 1988, 800 soil samples were taken from 160 sites across southern Manitoba. Samples were taken to a depth of 120 cm from various soil types, textures and slope positions. These samples were then analyzed for extractable chloride using a $AgNO_3$ titration procedure.

Soil chloride concentrations varied greatly among sites. Chloride concentrations in the top 60 cm ranged from a high of 1262 kg/ha in a St. Claude fine sandy loam to a low of 1.2 kg/ha in a Stockton loamy fine sand and a Souris loamy fine sand. Within sites chloride concentration also showed a high degree of variability. At one site chloride levels ranged from 16 to 1262 kg/ha over a distance of 0.5 km. Landscape position and depth in the profile did not have a consistent effect on chloride concentration. There was a higher frequency of low chloride levels in medium to course textured soils than in fine textured soils with the course textured soils being most variable in chloride concentration.

b) Effect of Chloride Fertilizer on Wheat and Barley

In the second phase initiated in 1989, field trials were established at five sites - one site on campus which rated high and four sites off campus which rated low to very low in chloride (the ratings are estimated according to the South Dakota guidelines of <66 kg/ha to 60 cm for low and <33 kg/ha to 60 cm for very low).

Two small sites sown to Katepwa wheat were established at Anola and Darlingford. Each trial consisted of five replicates of seven fertilizer treatments. Treatments included three fertilizer rates (0, 25, 50 kg/ha Cl) using two sources of broadcast fertilizer (KCl and NaCl). The seventh treatment was a seedrow application of 25 kg/ha Cl as KCl. Grain yield and quality were measured at these sites.

Three larger sites were also established - at Portage, Carman and the Point on campus. At Carman and Portage the experiment consisted of six replicates of 14 treatments arranged as a split plot design with Bedford barley and Katepwa wheat as main plots. Treatments consisted of three fertilizer rates (0, 25, 50 kg/ha Cl) with two sources of broadcast fertilizer (KCl and NaCl) and two disease inoculation treatments (inoculum and no inoculum). Two additional treatments consisting of 25 kg/ha Cl as KCl(seedrow placement) and two inoculation treatments (inoculum and no inoculum) were included. A similar design was used at the Point. However, in place of main plots of wheat and barley, main plots consisted of Bedford barley treated with common root rot inoculum and Bedford barley treated with spot blotch inoculum. Measurements taken at these three larger sites included plant counts at the one to three leaf stage, disease severity ratings at early heading and again at milky to mealy ripe stage, plant nutrient levels at the early heading stage, grain yield and grain quality measures.

The effect of chloride fertilization on wheat and barley was inconsistent in 1989. Plant counts, especially in wheat, were reduced by common root rot inoculum. There was no consistent effect of chloride on the severity of common root rot or spot blotch at any individual site. Grain yield responses to chloride fertilization were either very small or nonexistent, regardless of disease inoculation.

Environmental conditions of the 1989 growing season may well have had a significant effect on the results obtained. Conditions were such that disease development occurred rapidly early in the season but was brought to an abrupt halt by the hot, dry conditions which followed. If, in fact, a yield response to chloride application is a function of the disease suppressant action of chloride, the large influence which environment exerted on disease development may well have dominated over the relatively small influence of chloride.

References

Beaton, J. D., K. M. Pretty and J. L. Sanders. 1988. The chloride component of fertilizers can be beneficial. **In** Third Chemical Congress of North America, Toronto, Ont. June 5-10, 1988.

Beaton, J. D. and R. Speer. 1961. Influence of several moisture tension ranges and chloride levels on the yield and chloride content of bromegrass. J. Sci. Food Agric. 12:265-269.

Beaton, J. D. 1984. Crop responses to potassium chloride: due in part to chloride? p. 21-39. **In** Proc. of the 6th Manitoba-North Dakota Zero Tillage Workshop, Bismarck, ND. January 26-27. Manitoba-North Dakota Zero Till Farmers Association, Winnipeg, MB.

Christensen, N. W., R. J. Roseberg, M. Brett and T. L. Jackson. 1986. Chloride inhibition of nitrification as related to take-all disease of wheat. p. 22-39. **In** Chloride and crop production. Potash and Phosphate Institute Spec. Bull. No. 2. Atlanta, GA.

Fixen, P. 1987. Potassium and chloride effects on wheat yields and profitability. Better Crops. Summer 1987. p. 20-23.

Fixen, P. E. 1987. Chloride fertilization? Recent research gives new answers. Crops and Soils Magazine. 39(6):14-16.

Fixen, P. E., G. W. Buchenau, R. H. Gelderman, T. E. Shumacher, J. R. Gerwing, T. A. Cholick and B. G. Farber. 1986. Influence of soil and applied chloride on several wheat parameters. Agron. J. 78:736-740.

Goos, R. J., B. M. Holmes and B. E. Johnson. 1986. Effect of chloride fertilization on cereal diseases in North Dakota. p. 186-190. Proc of Manitoba Soil Science Society Meeting, Winnipeg, MB., Jan. 6-7, 1987. Manitoba Society of Soil Science.

Goos, R. J. 1986. Effect of KCl fertilization on small grains in North Dakota. p. 52-61. **In** Chloride and crop production. Potash and Phosphate Institute Spec. Bull. No. 2. Atlanta, GA.

Goos, R. J., B. E. Johnson and B. M. Holmes. 1987. Effect of potassium fertilizers on two barley cultivars differing in common root rot reaction. Can. J. Plant Sci. 67:395-401.

Maas, E. V. 1986. Physiological response of plants to chloride. p. 4-20. **In** Chloride and crop production. Potash and Phosphate Institute Spec. Bull. No. 2 Atlanta, GA.

Smiley, R. W. and R. J. Cook. 1973. Relationship between take-all and rhizosphere pH in soils fertilized with ammonium vs. nitrate-nitrogen. Phytopathology 63:882-890.

ZN AND P INTERACTIONS WITH SOIL NUTRIENTS IN FLAX GROWTH

C.A. GRANT AND L.D. BAILEY
Agriculture Canada, Brandon Research Station

INTRODUCTION

Flax is an oilseed crop grown on a large area in the Canadian prairies. Flax is extremely sensitive to Zn deficiency, which can lead to chlorosis and mainstem dieback of the plants. The combination of cool soil temperatures, high Ca and Mg content of soils and increased usage of P fertilizer occurring in the northern prairies could induce Zn deficiency on soils containing low levels of Zn. Therefore, the objectives of this study were:

(1) To determine the relationship between Ca, Mg, Zn and P concentration of soils and the dry matter yield and nutrient relations of flax.

(2) To determine the effect of varying soil concentrations of Ca, Mg, Zn and P on the fertilizer response of flax.

MATERIALS AND METHODS

Eight different calcareous Chernozemic soils were selected from Western Manitoba for each of two experiments for a total of 16 different soils. Three fertilizer treatments were applied:

(1) Control
(2) 100 kg P ha^{-1}, mixed with the soil
(3) 100 kg P ha-1 plus 12 kg Zn ha^{-1}, mixed with the soil

The P was applied as ammonium phosphate and the Zn was applied as zinc sulphate solution. The Zn was dissolved in water, sprayed onto the soil, and mixed thoroughly. The rate of broadcast P used would be comparable to that which would be used to increase soil levels for a residual effect. Nitrogen and sulphur were applied as ammonium nitrate and ammonium sulphate to balance the N and S applied with the P and Zn. Additional N and S plus K as KCl were applied to ensure that they did not limit yield. Fertilizers were blended thoroughly with the soil. An additional 100 mg kg^{-1} of N as NH_4NO_3 was dissolved in distilled water and watered into the soil surface after 4 wks of growth to ensure that N did not become limiting.

Treatments were replicated three times for a total of 72 pots per experiment. Flax plants were grown in 4 kg of soil in 15 x 15 x 20 cm wooden pots lined with plastic. Twenty seeds were sown 1.0 cm deep and the soil was watered to field capacity with oxine bensoate solution to avoid damping off. After emergence, plants were grown in growth chambers maintained at 16h light/8h dark with 16C day/10 C night. Soils were watered to field capacity with distilled water when the moisture content decreased to 70% of field capacity. Seedlings were thinned to 12 per pot after emergence and to 6 per pot after 4 wks of growth. Plants were harvested at 8 weeks (early bloom). Dry matter yield and tissue P, Zn, Mg and Ca were measured.

Ammonium acetate extractable Ca and Mg, DTPA extractable Zn and Mn, sodium bicarbonate extractable P, pH and conductance were measured in the soils (Table 1).

Table 1. Types, extractable Zn, Mn, P, Mg and Ca, pH and conductance of soils used in the study

SOIL	Zn	Mn	P	Mg	Ca	pH	Conductance
	------------------	------------------	μg g^{-1}	------------------	------------------		(mhos x 10^{-5})
EXPERIMENT 1							
1. Beresford CL	2.60	27.2	49.5	291	3075	7.48	9.3
2. Beresford CL	2.25	23.1	19.8	921	4305	7.33	16.7
3. Beresford CL	1.00	15.4	11.5	1159	5986	7.61	29.8
4. Druxman CL	1.22	19.2	20.5	394	3526	7.36	11.9
5. Justice CL	3.05	16.6	17.5	872	6724	7.71	22.0
6. Kleyson SiCL	1.83	18.5	48.0	646	6642	7.55	44.7
7. Miniota FSL	1.75	17.0	19.5	1798	4428	7.40	17.3
8. Newdale CL	2.99	24.0	26.5	672	5986	7.43	28.4
EXPERIMENT 2							
1. Beresford Cl	0.90	23.9	26.8	1491	7743	7.99	36.3
2. Justice CL	1.66	29.4	10.9	1162	5023	7.68	37.5
3. Newdale CL	1.14	28.2	11.2	951	5781	7.69	34.8
4. Newdale CL	2.42	27.7	32.3	1223	6074	7.77	34.3
5. Souris LFS	0.37	5.8	6.6	1973	2643	8.49	24.7
6. Waskada CL	0.66	25.8	22.9	602	3130	7.71	15.5
7. Waskada CL	0.68	28.6	9.0	532	5782	8.14	32.0
8. Waskada CL	0.77	21.1	7.8	628	5922	7.99	36.3

RESULTS AND DISCUSSION

(a) Effect of soil chemical parameters on flax dry matter yield and nutrient content

Correlation coefficients for the yield of flax that was not fertilized with Zn or P are shown in table 2. Yield increased as Zn in the soil increased but was not related to the soil level of P (Table 2). Yield decreased as soil Mg, pH and conductance increased. Conductance, pH and Mg in the soil were also correlated with one another.

The best fit regression equation for yield was:

Yield = 22.58 + 2.23 Zn - 0.01 Mg - 1.26 Ca/Mg (R^2=0.62)

In these soils, yield was affected positively by Zn and negatively by Mg. The negative term for the Ca/Mg ratio in the regression equation indicates that yield decreased at a decreasing rate as the soil Mg level increased.

Tissue concentration of P was decreased as dry matter yield increased. This demonstrates the effect of dilution. Tissue P was not influenced by either Zn or P content of the soil, however it tended to decrease with increasing Ca level and increase with increasing Mg and pH. This apparently reflects the effect of Mg and pH on dry matter yield and indicates that the negative effects of Mg and pH on yield are not due to interference with P availability. Tissue concentration of Zn was only influenced by pH level, indicating a reduction in Zn availability with increasing soil pH.

Table 2: Correlation coefficients among flax dry matter yield and tissue nutrient content and soil chemical composition.

	Yield	Tissue P	Tissue Zn
Yield	1.00	-0.46**	ns
Zn	0.52*	ns	ns
P	ns	ns	ns
Ca	ns	-0.33*	ns
Mg	-0.52**	0.55***	ns
pH	-0.57***	0.54***	-0.67***
Conductance	-0.38**	ns	ns

b) Effect of P and Zn fertilization on flax yield and nutrient content

The tendency for yield to increase as soil Zn increased indicated that a yield response to addition of fertilizer Zn was possible in these soils. When the influence of P and Zn fertilization on yield was examined, five patterns of response were apparent (Table 3).

(1) No response to either P or Zn application (5/16 soils). In these soils, yield was not limited by either P or Zn.

(2) Increase in yield due to P but no further increase due to Zn + P (1/16 soils). In this soil, yield was limited by P, but not by Zn.

(3) Yield not influenced by P but increased with Zn + P (4/16 soils). In these soils P was not deficient. Zn deficiencies were limiting yield.

(4) Yield maintained or increased with Zn + P but decreased with P alone (4/16 soils). In these soils P was high and Zn was marginal

Table 3. Dry matter yield of flax (g pot^{-1}) on various soil types and the effect of Zn and P fertilization, with P values determined through contrast analysis

EXPERIMENT 1

Treatment	Beresford 1	Beresford 2	Beresford 3	Druxman	Justice	Kleyson	Miniota	Newdale
Control	10.67	9.33	5.60	11.67	14.10	6.33	6.10	14.10
P broadcast	10.23	11.53	15.03	13.33	13.17	6.50	6.93	14.13
P broadcast + Zn	8.53	14.23	18.53	12.93	21.40	7.43	8.67	19.63
MSE	1.9023	1.3977	0.9897	2.2038	3.7938	1.2472	0.3702	7.3172
Contrasts								
Control vs P	ns[1]	0.0437	0.0001	ns	ns	ns	ns	ns
Zn vs No Zn (with P applied)	ns	0.0197	0.0325	ns	0.0007	ns	ns	0.0280
P broadcast with Zn vs without Zn	ns	0.0233	0.0026	ns	0.0008	ns	0.0082	0.0375

EXPERIMENT 2

Treatment	Beresford	Justice	Newdale 1	Newdale 2	Souris	Waskada 1	Waskada 2	Waskada 3
Control	9.62	4.17	5.92	5.04	1.62	14.65	4.73	3.83
P broadcast	13.15	3.09	6.31	3.86	0.87	13.47	3.85	5.09
P broadcast + Zn	13.57	7.84	7.02	5.02	4.12	15.45	8.26	5.67
MSE	1.5038	0.1387	0.4553	0.1387	0.1027	1.5907	2.5817	0.9968
Contrasts								
Control vs P	0.0368	ns	ns	0.0118	ns	ns	ns	ns
Zn vs No Zn (with P applied)	ns	0.0001	0.0075	0.0376	0.0001	ns	ns	ns
P broadcast with Zn vs without Zn	ns	0.0001	ns	0.0050	0.0001	ns	0.0099	ns

---

[1] ns indicates not significant at $P \leq 0.05$.

Table 4. Phosphorus content of flax tissue (%) on various soil types and the effect of Zn and P fertilization, with P values determined by contrast analysis

EXPERIMENT 1

Treatment	Soil Type Beresford 1	Beresford 2	Beresford 3	Druxman	Justice	Kleyson	Miniota	Newdale
Control	0.29	0.24	0.17	0.21	0.23	0.34	0.30	0.27
P broadcast	0.42	0.42	0.34	0.45	0.48	0.40	0.39	0.42
P broadcast + Zn	0.39	0.32	0.23	0.36	0.26	0.32	0.30	0.29
MSE	0.00247	0.00283	7.1x10-4	0.00184	0.0020	5.1x10-4	5.7x10-4	0.0025
Contrasts								
Control vs P	ns[1]	ns	0.0015	0.0017	0.0025	ns	ns	0.0379
Zn vs No Zn (with P applied)	ns	ns	0.0063	ns	0.0006	0.0060	0.0213	0.0175
P broadcast with Zn vs without Zn	ns	ns	0.0011	0.0383	0.0003	0.0022	0.0015	0.0112

EXPERIMENT 2

Treatment	Soil Type Beresford	Justice	Newdale 1	Newdale 2	Souris	Waskada 1	Waskada 2	Waskada 3
Control	0.13	0.37	0.23	0.37	0.92	0.30	0.20	0.23
P broadcast	0.32	0.72	0.41	0.46	1.15	0.58	0.55	0.35
P broadcast + Zn	0.23	0.27	0.29	0.38	0.49	0.36	0.23	0.28
MSE	7.4x10-4	0.0039	0.0021	3x10-4	0.0076	0.0027	0.0035	0.0010
Contrasts								
Control vs P	0.0008	0.0016	0.0048	0.0028	ns	0.0038	0.0022	0.0416
Zn vs No Zn (with P applied)	ns	0.0001	0.0066	0.0002	0.0001	0.0017	0.0024	ns
P broadcast with Zn vs without Zn	0.0045	0.0001	0.0138	0.0002	0.0001	0.0010	0.0002	0.0253

---

[1] ns indicates not significant at $P \leq 0.05$.

Table 5. Zinc content of flax tissue (µg g^{-1}) on various soil types and the effect of Zn and P fertilization, with P values determined by contrast analysis

EXPERIMENT 1

Treatment				Soil Type				
	Beresford 1	Beresford 2	Beresford 3	Druxman	Justice	Kleyson	Miniota	Newdale
Control	21.0	30.8	37.0	29.0	17.5	24.8	28.2	17.8
P broadcast	19.0	28.8	27.7	19.0	15.3	28.0	18.8	16.0
P broadcast + Zn	33.0	34.0	22.3	39.5	23.7	30.0	36.2	24.5
MSE	7.82	63.49	8.62	15.68	6.41	16.07	5.30	12.21
Contrasts								
Control vs P	ns	ns	0.0005	0.0076	ns	ns	0.0428	ns
Zn vs No Zn (with P applied)	0.0001	0.0156	0.0062	0.0001	0.0001	0.0400	0.0001	0.0001
P broadcast with Zn vs without Zn	0.0003	ns	ns	0.0002	0.0038	ns	0.0001	0.0173

EXPERIMENT 2

Treatment				Soil Type				
	Beresford	Justice	Newdale 1	Newdale 2	Souris	Waskada 1	Waskada 2	Waskada 3
Control	18.4	12.4	21.5	16.0	9.7	10.7	12.4	15.5
P broadcast	10.8	9.0	14.7	14.0	8.2	9.2	10.1	12.2
P broadcast + Zn	19.1	19.6	22.1	20.7	18.4	26.8	18.9	24.0
MSE	3.70	3.97	4.57	1.10	7.43	7.38	27.19	1.32
Contrasts								
Control vs P	0.0016	ns	0.0093	ns	ns	ns	ns	ns
Zn vs No Zn (with P applied)	0.0001	0.0001	0.0001	0.0001	0.0018	0.0001	0.0024	0.0001
P broadcast with Zn vs without Zn	0.0008	0.0002	0.0029	0.0001	0.0041	0.0001	ns	0.0001

---

[1] ns indicates not significant at $P \le 0.05$.

or deficient. Application of P increased P levels in the tissue to high levels and induced or aggravated a Zn deficiency, causing yield reductions, which could be counteracted by application of Zn.

(5) Yield increased with P and increased further with Zn + P (2/16 soils). In these soils both P and Zn were low. Adding P corrected the P deficiency, but Zn still limited yield, so yield increased further with application of Zn + P.

Applications of P consistently increased while application of Zn with P consistently decreased P level of the tissue (table 4). Application of Zn increased the concentration of Zn in the tissue (Table 5). Application of P tended to decrease the concentration of Zn in the tissue. This was true regardless of the effect of P upon dry matter yield, so dilution was not a factor. Phosphorus therefore appeared to interfere directly with the accumulation of Zn by the flax shoots.

Application of P that increased the P level in the tissue above 0.46% led to consistent but nonsignificant decreases in yield and reduced the level of Zn in the tissue to low levels. Tissue level of 0.46% is not excessively high, but P may have reduced yield by interfering with the ability of the plant to utilize Zn. Such Zn-P interactions have been reported frequently. The likelihood of a yield response to applied Zn was greater when the Zn concentration in the tissue was reduced due to effective P fertilization.

c) Effect of soil chemical characteristics on fertilizer response

Correlation coefficients were calculated between increase in dry matter yield due to fertilizer applications and the soil chemical parameters. Regression equations for yield increases were also calculated, considering soil Zn, P, Ca, Mg, Ca/Mg ratio, pH and conductivity.

Table 6: Correlation coefficients between increase in dry matter yield of flax due to fertilizer application and the chemical composition of the soil and tissue.

	P	P + Zn	Zn
Soil P	ns	-0.49**	-0.30*
Soil Zn	ns	-0.41**	ns
Soil Ca	ns	ns	ns
Soil Mg	ns	0.47**	0.51**
Soil pH	ns	0.35*	0.61***
Conductance	ns	ns	ns
Tissue P	-0.34*	0.35*	0.75***
Tissue Zn	0.65***	ns	-0.45**
Tissue Ca	ns	-0.38**	ns
Tissue Mg	ns	0.45**	0.81***

Increase in dry matter yield due to application of P fertilizer alone was not related to any soil parameter measured (Table 6). The best fit regression equation for the increase in yield due to broadcast P was:

Increase = 535.36 -1.70 P -62.95 pH (R^2=0.21)

So, response to P alone did decrease as soil P increased and as the soil pH increased. However, little of the variability was explained by this equation, and so it seems other factors not considered in the study had a large influence on response to fertilizer P. Yield response to broadcast P decreased as tissue levels of P increased and increased as tissue levels of Zn increased, indicating the importance of adequate tissue Zn in ensuring a good response to P fertility.

Increase in yield due to application of P and Zn together decreased as soil P and soil Zn increased (Table 6). Response also increased as soil Mg and soil pH increased. This indicates that Zn and P availability were reduced at higher levels of Mg and pH. The equation for increase due to broadcast P + Zn was:

$$\text{Increase} = 53.87 - 2.09\ P + 0.050\ Mg\ (R^2=0.34)$$

Again, this equation explains little of the variability, as can be seen from the low r-square value. However, it reinforces the importance of P and Mg level in determining the response to fertilization. Yield response to application of P plus Zn also decreased as tissue Ca level increased and increased as tissue Mg increased, indicating that Mg may interfere with the availability of Zn and/or P (Table 6).

Yield response to the Zn component of the Zn+P, calculated as increase due to Zn+P minus increase due to P alone, decreased as the P level in the soil increased and increased as the Mg and pH level in the soil increased (Table 6). Considering the Zn-P interaction which is often reported, one would have expected a greater response to Zn fertilizer when the P level in the soil was high. However, when the regression equations were calculated, the P level in the soil did not come into play.

$$\text{Increase} = -1027.70 + 0.0683\ Mg + 131.24\ pH\ (R^2=0.53)$$

This again indicated that availability of Zn decreased as Mg and pH levels increased, resulting in a greater response to fertilizer Zn. Yield response to application of Zn with P increased as tissue P and Mg levels increased and decreased as tissue Zn level increased. Accumulation of P and/or Mg in the tissue may interfere with availability of Zn, increasing the requirement for fertilizer Zn.

Tissue analysis on the flax demonstrates that interpretations of "deficiency" or "sufficiency" cannot be based strictly on plant tissue levels. Responses to Zn were observed where tissue levels were well above the deficiency range (Tables 3 and 5). In other soils, responses were not observed even when tissue levels were low. Responses to P were not observed if tissue P was in the sufficiency range, but responses frequently did not occur when tissue P levels were in the deficiency range (Tables 3 and 4).

CONCLUSIONS

Dry matter yield of flax increased with increasing soil Zn and decreased with increasing soil Mg and pH. The increase in yield due to application of Zn with P was more effectively predicted by Mg and pH level in the soil than by either Zn or P level. Although yield response to Zn decreased with increasing Zn level in the tissue, the strongest simple correlation was between Zn response and Mg level in the tissue. The correlation between Zn response and P level in the tissue was also high. Therefore, high levels of P and Mg in the tissue appear to interfere with Zn utilization by the plant and lead to higher requirements for Zn to produce optimum dry matter yield.

Long-term Bioavailability of Cu-EDTA and $CuSO_4$ in an Organic Soil

M.D. Thomlinson & G.J. Racz
University of Manitoba

R.E. Dowbenko
Sherritt-Gordon Fertilizers

INTRODUCTION

Previous research indicated good yield responses to both $CuSO_4$ and Cu-EDTA on organic soils when these fertilizers were broadcast and incorporated thoroughly into the soil prior to planting. Barnes and Cox (1973), for example, found no difference in crop response when equal rates of Cu as $CuSO_4$ and chelated Cu were broadcast and incorporated. Younts (1964) also indicated that $CuSO_4$ and Cu-EDTA were equally effective in increasing yield of wheat. In contrast to the findings noted above, chelated forms of Cu, due to their greater solubility and mobility, appear to offer increased Cu efficiency (Gartrell 1981). Varvel (1983), for example, showed Cu chelates to be superior to $CuSO_4$ for most methods of application.

Recent work in Manitoba (Dowbenko 1989) showed that Cu applied as Cu-EDTA to an organic soil was not as readily extracted by DTPA as was Cu applied as $CuSO_4$ (Table 1). The DTPA extractions were conducted at various times after fertilization with 5.0 Kg Cu ha^{-1} as $CuSO_4$ or Cu-EDTA. Dowbenko (1969) also compared the effectiveness of 5 Kg Cu ha^{-1} of $CuSO_4$ and Cu-EDTA) thoroughly mixed with the soil, in increasing barley grain yield on an organic soil in a growth chamber experiment. Yield of grain was not significantly different, but the Cu content of the grain with Cu-EDTA was significantly less than that with $CuSO_4$ (Table 2). The grain produced with the copper chelate had a shrivelled appearance (indicative of Cu deficiency) whereas the grain produced with $CuSO_4$ was reasonably plump. It was also noted in this study that the plants contained about equal concentrations of Cu at the heading stage regardless of the source of Cu. It was postulated that the Cu-EDTA may have been as bioavailable as $CuSO_4$ during the early stages of growth but decreased in bioavailability in relation to that of $CuSO_4$ during the grain filling and maturation period. (i.e.) $CuSO_4$ had a better long-term bioavailability than Cu-EDTA.

Since Cu-EDTA was found to be less effective than $CuSO_4$ in producing quality grain and the grain produced with Cu-EDTA had lower concentrations of Cu than grain produced with $CuSO_4$, studies were conducted to evaluate more fully the long-term bioavailability of Cu-EDTA and $CuSO_4$. The DTPA extractability of Cu as applied Cu-EDTA and $CuSO_4$, as a function of time, was also assessed.

MATERIALS AND METHODS

Soil was obtained from the surface layer of a Terric Mesisol (Table 3) and thoroughly mixed. Samples of moist soil, equivalent to 275g oven-dry weight, were placed into pots 12 cm in height and of 15 cm diameter.

Nitrogen at a rate of 150 Kg Nha^{-1} as NH_4NO_3, phosphorus at a rate of 25 Kg P ha^{-1} as $NH_4H_2PO_4$ and potassium as KCl at a rate of 125 Kg k ha^{-1} (area bases) was added to the soil in each pot. The soil in each pot was removed and spread thinly on a sheet of paper. The fertilizers, applied as solutions, were sprayed onto the soil. The soil was then thoroughly mixed and returned to the pot.

Cu as $CuSO_4 5H_2O$ or Cu-EDTA was applied as solutions at a rate 0 or 5 Kg ha^{-1} (area bases). Two methods of Cu application, referred to as banded or mixed, were selected. Cu, when banded, was applied in a very narrow band across the center of the soil in the pot using a 10-ml pipette. A 1.5 cm layer of soil was first removed from the pot, the band of fertilizer applied and the soil replaced. Cu, when mixed with the soil, was applied as described for method of application of N, P and K. After fertilization, the soils were watered to field capacity moisture content using distilled water and the pots placed into a growth chamber. The soils were incubated in the growth chamber for 0, 3, 6, 9 or 12 wk.

Short-term plant growth studies were conducted to evaluate the bioavailability of the applied Cu after each incubation period. Twenty barley seeds (Hordeum vulgare var Heartland) were placed at a depth of 1.5 cm in a row across the center of pots lined with cloth mesh and containing the equivalent of 100 g of oven-dry nonfertilized soil. The soils were wetted to field capacity moisture content and the plants were grown for a period of 10 d and then thinned to 14 plants pot^{-1}. The soil plus plants were then carefully removed from the pot by lifting on the cloth mesh and placed on top of the soil in the pots with the various copper treatments. Placement of the soil plus plants was such that the row of plants were above the band of Cu fertilizer. The plants were grown for a period of 3 wk, harvested, dried and weighed and analyzed for Cu content using atomic absorption spectrophotometry.

A total of 5 harvests, one harvest corresponding to each incubation period, was obtained at 3, 6, 9, 12 or 15 wk after Cu fertilization. All treatments were replicated three times.

A 16 hr photoperiod with a light intensity of 500 micro-Einsteins $m^{-2}s^{-1}$, and a day/night temperature regime of 22/16 C was maintained for all studies. Water content of the soils during incubation and plant growth studies was maintained near filled capacity moisture content by daily application of distilled water.

Soil, after harvest of the barley, was removed from the pots, thoroughly mixed, air-dried and analyzed for DTPA-extractable Cu (Lindsay and Norvell 1978). Since soil samples were obtained after harvest of the barley, samples were obtained at 3, 6, 9, 12 and 15 wk after Cu fertilization.

RESULTS AND DISCUSSION

Application of $CuSO_4$ and Cu-EDTA increased the DTPA-extractable Cu content of soils (Figure 1, and Table 4). DTPA-extractable Cu content of soils treated with $CuSO_4$ was greater than that of soils treated with Cu-EDTA at all sampling times. The results obtained are similar to those reported by Dowbenko (1989). The reason(s) for the differences in extractability of Cu applied as $CuSO_4$ and Cu-EDTA is not known and additional work needs to be conducted to elucidate the mechanisms responsible for the differences observed. Method of placement of the fertilizer had only minor effects on DTPA-extractable Cu. It should be noted, however, that after harvest of the barley, the soil in each pot was thoroughly mixed prior to analysis.

Yield of barley, obtained 3 wk after Cu application (first harvest), was similar with $CuSO_4$ and Cu-EDTA and higher with Cu fertilizer than without (Figure 2, Table 4). Yield with Cu-EDTA, when incubation times were greater than 3 wks, was similar to that without Cu fertilizer. Yields with $CuSO_4$ were always greater than that without Cu or with Cu-EDTA when incubation times were greater than 3 wk. Method of placement of the fertilizer had no or little effects on yield.

Concentrations of Cu in plant tissue generally followed the order: Cu-EDTA mixed > Cu-EDTA banded $\gtrsim$ $CuSO_4$ banded $\gtrsim$ no cu. (Figure 3 and Table 4). Cu uptake (ug pot^{-1}) by plants followed trends similar to that noted for Cu concentration in plants though yield with $CuSO_4$ was usually greater than with Cu-EDTA or without Cu (Figure 4 and Table 4). Concentrations of Cu in plants and uptake of Cu by plants when the $CuSO_4$ was banded was very low and about equal to that of plants not treated with Cu. The low utilization of Cu from the banded $CuSO_4$ is likely due to the limited root to fertilizer contact in such treatments. Cu, applied as $CuSO_4$ in a band, is very immobile in soils (Barber 1980) and thus the Cu remains in a very small micro region near the site of application. The limited volume of soil fertilized would limit the amount of roots in contact with the fertilizer and hence uptake. Uptake of Cu by plants when Cu-EDTA was added as a band or when the Cu fertilizers were mixed with the soil was much higher than without Cu. Due to the mobility of Cu applied as Cu-EDTA and/or the mixing of the Cu fertilizer with the soil, the root to fertilizer contact would be increased due to the larger volumes of soil fertilized. Gilkes and Sadleir (1979) and Jarvis and Whitehead (1981) indicated that the uptake of Cu was, to a large degree, dependent upon root exploration and interception. As such, methods of application which increase root to copper contact would generally provide the greatest efficiency of soil applied Cu fertilizers. The results obtained in this study are consistent with those of the authors cited above.

The yield of barley was not related to concentrations of Cu in plant tissues. Concentrations of Cu in plant tissues were usually higher with Cu-EDTA than with $CuSO_4$. Yet, yields were higher with $CuSO_4$ than with Cu-EDTA. Possible reasons for the discrepancy between yield and Cu content of the tissue are:

(1) A yield response to sulfur. Sulfur was added when $CuSO_4$ was used as a Cu source but not when Cu-EDTA was applied. Thus, if a sulfur deficiency was present, yield with $CuSO_4$ would be expected to be greater than with Cu-EDTA. However, the SO_4-S content of the soil was very high (870 ug g^{-1}) and adequate sulfur levels were present in both the $CuSO_4$ and Cu-EDTA treated soils. The amount of sulfur added with the $CuSO_4$ was small in comparison to amounts present in the soil. Also, plant analysis showed that the sulphur content of plants grown with $CuSO_4$ and Cu-EDTA were the same ($\approx$0.30%). Thus, a sulfur deficiency probably did not exist and differences in yield noted for the $CuSO_4$ and Cu-EDTA treatments were not due to a sulfur deficiency.

(2) Increased tillering of plants due to a Cu deficiency. Cu deficiency in barley has been shown to result in proliferation of tillering of plants with the result that vegetative yields at times may be lower with Cu than without (Snowball and Robson 1984). However, the Cu content of plants with the Cu-EDTA banded and the $CuSO_4$ mixed with the soil were generally similar and adequate for normal plant growth. Thus, differences in tillering cannot account for the differences in vegetative yield between plants treated with $CuSO_4$ and Cu-EDTA.

(3) Uptake of Cu as Cu-EDTA. It is possible that in these studies Cu as Cu-EDTA entered the plant roots, was translocated to the tops of the plants but then was not metabolized for growth functions of the plant. If this occurred, Cu concentrations in the plant (present as Cu-EDTA) could be high yet growth would not be increased. It is interesting to note that the results obtained by Dowbenko (1989) (Table 2) appears to reflect a similar phenomena. Cu concentrations in the plant at the heading stage were high for plants treated with $CuSO_4$ and Cu-EDTA but only $CuSO_4$ increased the Cu content of the grain and grain quality. Whether or not plants absorb intact metal chelates is a controversial question and definitive information on whether or not metal chelates are absorbed by roots was not found in the literature. Although the uptake of Cu as Cu-EDTA by plants treated with Cu-EDTA cannot be confirmed from these studies, it would appear from the data obtained that the possibility of Cu uptake by plants as Cu-EDTA should be investigated.

CONCLUSIONS

DTPA - extractable Cu concentrations in $CuSO_4$ treated soils was greater than that of soils treated with Cu-EDTA at equivalent rates.

$CuSO_4$ and Cu-EDTA both increased yield when soils were incubated for a period of 3 wk. However, $CuSO_4$ was effective and Cu-EDTA was not effective in enhancing yield when soils were incubated for periods of 3 to 15 wk. Cu concentration in plant tissues and Cu uptake (ug pot^{-1}) were usually greater with Cu-EDTA than with $CuSO_4$. Increases in Cu content of tissues was reflected in yield increases when $CuSO_4$ was added. In contrast, yield did not increase despite increases in Cu content of plant tissues when Cu-EDTA was added. The results obtained suggested that Cu as Cu-EDTA may have been taken up by the plant but not metabolized for growth functions.

LITERATURE CITED

Barber, S.A. 1980. Soil-plant interactions in the phosphorus nutrition of plants. __In__: The Role of Phosphorus in Agriculture. E.C. Sample and E.J. Kamprath (Eds.). Amer. Soc. of Agron. Madison, WI.

Barnes, J.S. and F.R. Cox. 1973. Effects of copper sources on wheat and soybeans grown on organic soils. Agron. J. 65:705-708.

Dowbenko, R.E. 1989. Long term effect of copper sulfate fertilization of organic soils on yield of barley and DTPA-extractable soil copper levels. M.Sc. Thesis, Dept. of Soil Sci., University of Manitoba, Winnipeg, MB.

Gartrell, J.W. 1981. Distribution and correction of copper deficiency in crops and pastures. In: Copper in Soils and Plants. J.F. Loneragan, A.D. Robson and R.D. Graham (Eds.). Academic Press. Sydney.

Gilkes, R.J. and S.B. Sadleir. 1979. The influence of placement geometry on the effectiveness of copper superphosphate. Aust. J. Soil Res. 17:1-8.

Jarvis, S.C. and D.C. Whitehead. 1981. The influence of some soil and plant factors on the concentration of copper in perennial rye grass. Plant and Soil 23:275-286.

Lindsay, W.L. and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci. Soc. Amer. J. 42:421-428.

Snowball, K. and A.D. Robson. 1984. Comparison of the internal and external requirements of wheat, oats, and barley for copper. Aust. J. Agric. Res. 35:359-365.

Varvel, G.E. 1983. Effect of banded and broadcast placement of Cu fertilizers on correction of Cu deficiency. Agron. J. 75:99-101.

Younts, S.E. 1964. Response of wheat to rates, dates of application, and sources of copper and to other micronutrients. Agron. J. 56:266-269.

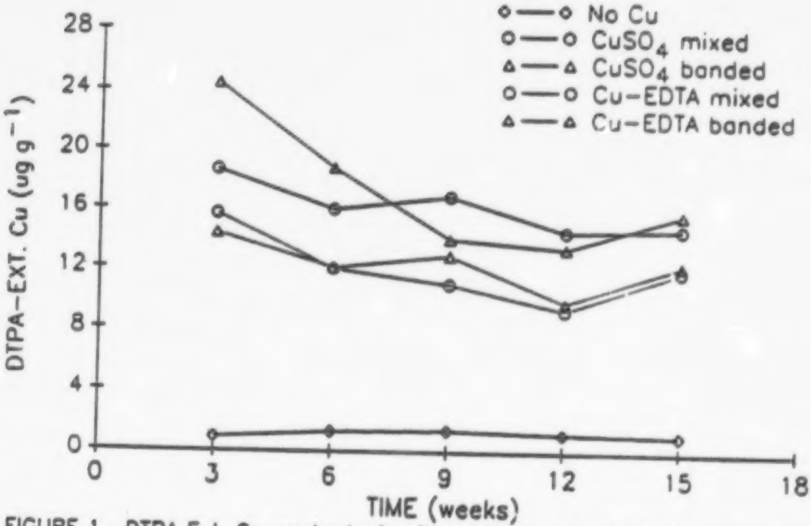


FIGURE 1. DTPA Ext. Cu content of soil as affected by Cu fertilization and period of time after fertilization.

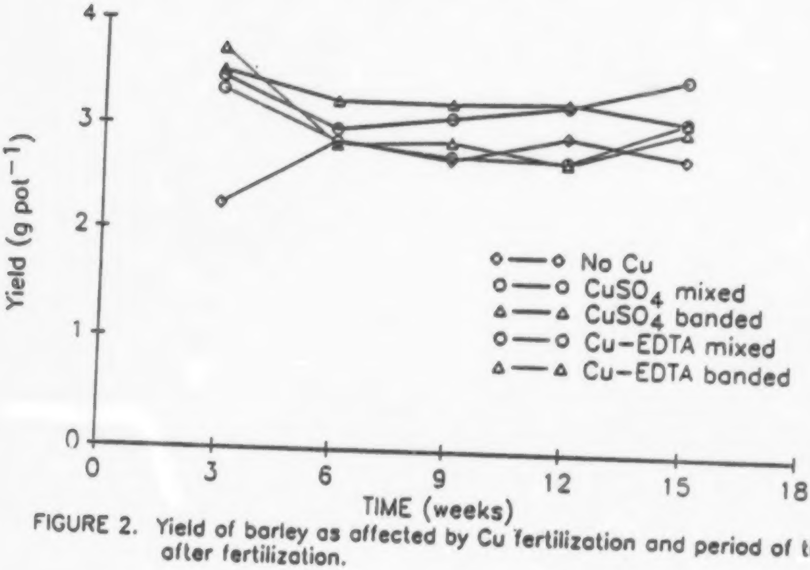


FIGURE 2. Yield of barley as affected by Cu fertilization and period of time after fertilization.

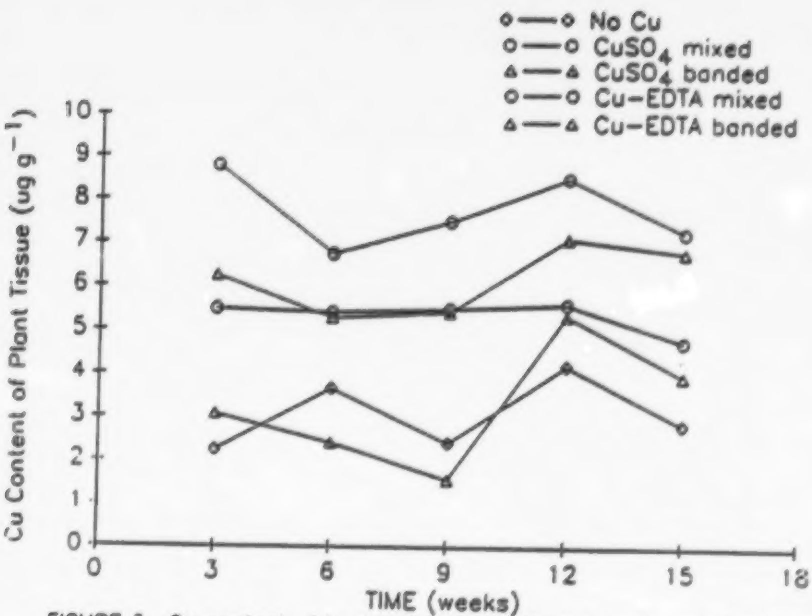


FIGURE 3. Cu content of barley tissue as affected by Cu fertilization and period of time after fertilization.

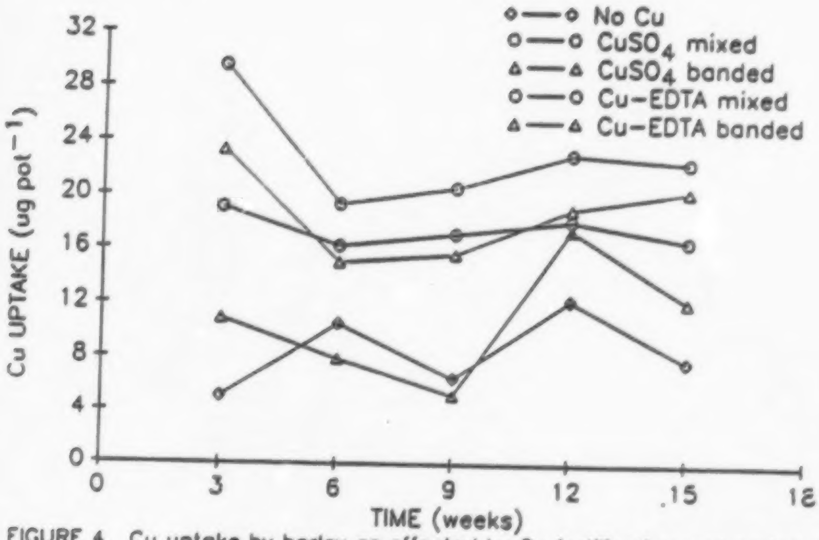


FIGURE 4. Cu uptake by barley as affected by Cu fertilization and period of time after fertilization.

Table.1 DTPA-Extractable Cu as affected by $CuSO_4$or Cu-EDTA fertilization (Dowbenko 1989)

Time (days)	DTPA-Ext. Cu (ug g^{-1}) $CuSO_4$ added	 Cu-EDTA added
50	10.0	3.7
82	7.4	3.5
96	13.0	3.2
110	10.0	4.2
124	6.7	4.2
138	10.0	5.3

Table 2. Affect of Cu Source on grain yield and Cu content of grain and plant tissue at the heading stage.

Treatment (kg Cu ha^{-1})	Yield of grain (g pot^{-1})	Cu Content of grain (ug g^{-1})	Cu content of plant at heading (ug g-1)
0.0	3.6	1.3	4.3
5.0 as Cu-EDTA	15.9	1.4	9.5
5.0 as $CuSO_4$	14.7	3.4	8.3

Table 3. Some characteristics of soil used.

pH	6.6
NO_3-N (ug g^{-1})	103.0
$NaHCO_3$-Ext. P (ug g^{-1})	2.2
CH_3COOH-Ext. K (ug g^{-1})	10.0
SO_4-S (ug g^{-1})	870.0
Conductivity (ds m^{-1})	1.3
DTPA-Ext. Cu (ug g^{-1})	0.9
Inorganic Carbonates	absent

Table 4. DTPA-Extractable Cu content of soils, yield and Cu content of barley as affected by Cu fertilization and period of time after fertilization.

	Time (wks)	No Cu	$CuSO_4$ mixed	$CuSO_4$ banded	Cu-EDTA mixed	Cu-EDTA banded
DTPA-EXT Cu(ug g^{-1})	3	0.9	18.7	24.5	15.7	14.4
	6	1.3	16.0	18.8	12.0	12.1
	9	1.4	16.9	14.0	11.0	12.9
	12	1.2	14.5	13.4	9.3	9.8
	15	1.1	14.7	15.7	11.9	12.3
Yield (g pot^{-1})	3	2.25	3.47	3.53	3.35	3.73
	6	2.87	2.98	3.25	2.86	2.83
	9	2.70	3.10	3.24	2.73	2.87
	12	2.93	3.23	3.26	2.70	2.68
	15	2.74	3.50	3.09	3.10	3.00
Cu Content (ug g^{-1})	3	2.25	5.50	3.08	8.80	6.25
	6	3.67	5.42	2.42	6.75	5.30
	9	2.42	5.50	1.58	7.50	5.42
	12	4.20	5.61	5.35	8.50	7.10
	15	2.85	4.75	3.96	7.24	6.78
Cu Uptake (ug pot^{-1})	3	5.10	19.10	10.90	29.50	23.30
	6	10.50	16.20	7.90	19.30	15.00
	9	6.50	17.10	5.20	20.50	15.60
	12	12.30	18.10	17.40	23.00	19.00
	15	7.80	16.60	12.20	22.40	20.30

Analysis of Phosphate Transport in Soil

C.M. Cho

Department of Soil Science
University of Manitoba

INTRODUCTION

It is generally understood that the water soluble form of phosphate in the applied fertilizer phosphate interacts with soil constituents and becomes unavailable or very slowly available to crops. The term, interaction, is commonly used without really understanding the nature of interaction. A common functional relation that describes the magnitude of interaction with the measurable variable, such as concentration, is either a Langmuir or Freundlich adsorption isotherm.

In order to describe the phosphate transport in soil, a transport equation is formulated by combining the continuity relation with the adsorption isotherm. In order to refine the transport equation to include a possible time-dependent rate process additional term is generally added to the transport equation. Such transport equations seem to describe the phosphate behaviour reasonably well provided proper choice of parameters were made.

Experimental evidences are abundant that point to the fact that the adsorbed cations are responsible for the precipitation of added phosphate in soil. In other words, the exchangeable cation, especially Ca^{++} in calcareous soil and Al^{+++} and Fe^{+++} in acidic soils, are responsible for the precipitation of added phosphate. For example, a soil with 200 m mol (+) kg^{-1} (20 meq/100g) of CEC would contain approximately 8000 kg of exchangeable Ca^{++} per hectare-15 cm of soil if the exchange site is saturated with Ca^{++} and this corresponds to 0.4% on the soil basis. On the other hand, if we assume that approximately 0.1 - 0.5% of the solid $CaCO_3$ is active because it is exposed on the surface of $CaCO_3$ particle, then the active Ca^{++} expressed on the soil basis would be only 0.005 - 0.025% if the soil contained 5% $CaCO_3$. The importance of exchangeable ion becomes very obvious. However, none of the phosphate transport model so far included the effect of exchangeable cation upon retardation of phosphate transport in soil.

In this presentation on the theory of phosphate transport in calcareous soils, a phosphate transport model will be presented based on the assumtion that the exchangeable Ca^{++} is primarily responsible for precipitation of applied phosphate. A system of transport equations will be formulated, solved, physically interpreted and inference will be made.

MODEL FORMULATION

The inclusion of the exchangeable ion into the phosphate transport model requires at least 4 additional transport equations in addition to the phosphate transport equation itself. The phosphate ion has an associated cation because of the requirement of electro-neutrality. Thus the transport equation for cation is needed. The cation participates in the ion-exchange process and the exchangeable ion, say Ca^{++}, would be released into soil solution. Thus the transport equation for Ca^{++} is needed. The released Ca^{++} and phosphate interact to form solid $CaHPO_4$ and produces H^+, thus the H^+ transport equation has to be included to fully describe the phosphate transport process. Experimental evidences are abundant to indicate that pH of the media decrease as precipitation occurred. In addition, carbonate equilibria can not be disregarded since the precipitation of desorbed Ca^{++} as $CaCO_3$ with the production of H^+ can take place in alkaline media. The inclusion of carbonate transport equation makes up the minimum number of five transport equations needed to describe the phosphate transport in soil.

These equations interact each other through ion exchange, precipitation, production, ionic transformation and pH interaction. The cation and exchangeable Ca^{++} interact each other through ion exchange reaction. The desorbed Ca^{++} interacts with phosphate and carbonate and precipitates. Through this precipitation, H^+ ion is produced, and the magnitude of H^+ production is pH dependent. Carbonate in soil solution can be replenished from the soil atmosphere and this is dependent upon local pH and partial pressure of CO_2.

Formulation of transport equations for the system as complex as above is not an easy task without some approximations and assumtion. Equilibrium parameters such as dissociation constants and solubility products are readily available. However, the rate processes of ion exchange and precipitation reactions are not known. It is, thus, assumed that the ion-exchange process is instantaneous while the precipitation reactions are second order with residual concentrations governed by the solubilities, which are pH dependent.

The proposed five transport equations are made up as follow.

The cation transport equation contains ion exchange term.

The Ca^{++} equation contains ion exchange, second order precipitation reaction terms for $CaHPO_4$ and $CaCO_3$.

The phosphate equation contains second order precipitation for $CaHPO_4$ and Langmuir type adsorption on $CaCO_3$.

The H^+ equation has production terms due to second order reaction above. Estimated buffering action above pH near neutral is included.

An anion, such as $CO_3^{=}$, transport equation is generally needed if any salts which might interact with desorbed Ca^{++} are mixed with phosphate. Such equation might contain second order precipitation term.

The system of differential equations can not be solved analytically. Numerical technique known as Crank-Nicholson method in combination with iterative approximation was chosen to solve the equations. A number of parameters such as diffusion coefficient, CEC, solubility products are needed to solve the equations. The values chosen for the calculation are as close to the published or real figures. The boundary conditions were chosen to represent the situation in which phosphate was applied to the soil surface. The soil is assumed to contain no ion other than Ca^{++} which is present only in exchangeable form.

RESULTS

Concentration profiles of cation, phosphate and desorbed Ca^{++} in the absence of any precipitation reaction at 33 hrs. are presented in Fig. 1. The distribution patterns were obtained using diffusion coefficient of 0.1 mm^2/min, CEC of 20 meq/100g and there was no Ca^{++} in the solution at the onset the initiation. Constant boundary condition was used for cation and phosphate but no-flux surface boundary condition was used for desorbed Ca^{++}. The cation replaced Ca^{++} from the exchanger and consequently its concentration decreased with depth as compared to phosphate. There is a large concentration of desorbed Ca^{++} and its concentration is around 180 m mol/L near the soil surface. If Ca^{++} in the exchanger phase (20 meq/100g) is all replaced by the cation then the concentration would have been 600 m mol/L. It is noticed from the distribution pattern that the desorbed Ca^{++} and applied phosphate coexists within the same location. It is, therefore, immediately concluded that the phosphate and desorbed Ca^{++} would form a precipitate if condition is favourable for the precipitation to occur.

When a condition was chosen so that precipitation of CaH_2PO_4 would occur, a result similar to that shown in Fig. 2 was obtained. In constructing the result, it was assumed that the soil contained 5 % free $CaCO_3$ which contributed 30 m mol/L of adsorbable site for phosphate and the reaction rate of $CaHPO_4$ formation was second order with rate constant of 0.001 /m mol-min.

The cation applied on the surface diffused into the soil and replaced the exchangeable Ca^{++}. The concentration distribution of cation is very similar to that shown in Fig. 1. However, the distribution pattern of desorbed Ca^{++} was quite different from the previous result (Fig. 1). On the whole, the concentration was lower indicating that the desorbed Ca^{++} was removed from the solution, especially so near the soil surface. Comparison of phosphate distribution between Fig. 1 and 2 also reveal that phosphate was removed from the solution. The decreases in the phosphate and Ca^{++} are shown in the form of $CaHPO_4$ precipitate.

The original soil pH was chosen to be 8.3 and the fertilizer was assumed to have pH 7. Since the Pk_2 of phosphate is 7.2, there is abundant $HPO_4^{=}$ form which can combine with desorbed Ca^{++}. The formed $CaHPO_4$ near the soil surface is very high, around 420 m mol/L if the amount precipitated is expressed in solution unit. The precipitate decreased very rapidly with depth at the surface and then gradually decreased with depth up to where the phosphate has penetrated. The result of pH distribution indicated that the pH has dropped from 8.3 to the minimum of around 4.6 near 10 mm depth and gradually climbed up to 8.3 at 50 mm depth. The lowering of pH due to precipitation of phosphate decreases the further precipitation of phosphate as the fraction of $HPO_4^{=}$ is decreased.

The distribution of phosphate and carbonate when urea was mixed with phosphate and applied on the soil surface is shown in Fig. 3. The calculation was initiated to observe the effect of hydrolysis products of urea, ammonium and carbonate, upon phosphate transport characteristics. It is assumed that urea actually behaved like ammonium carbonate and had pH 9.4 so that there are considerable amount of free ammonia which can diffuse into soil with larger diffusion coefficient than regular salt or ionic forms. The larger diffusion coefficient of ammonia makes the penetration of ammonia deeper into the soil and this, in turn, is converted to ammonium and hydroxide ions. The ammonium ion is capable of replacing the exchangeable Ca^{++} and this is ready to react either with phosphate or carbonate.

Because of high pH and its buffering capability and the virtual absence of HPO_4^- under those circumstances, the H^+ production is rather minimal. Since the fractional concentration of $HPO_4^=$ is very high, the precipitation of $CaHPO_4$ is quite extensive and this virtually removed most of the desorbed Ca^{++} in solution near the soil surface. The fractional concentration of $CO_3^=$ is rather small at these pHs even though carbonate and phosphate concentration was the same. Consequently the precipitation of Ca^{++} as carbonate was rather insignificant as compared to $CaHPO_4$. This distribution pattern may change with time since carbonate can be continuously supplied from the atmosphere and precipitation of Ca^{++} as $CaCO_3$ would occur, even though it may be very slow, further away from the zone where phosphate is the dominating ion.

In case a higher amount of urea, or ammonium carbonate, was mixed with phosphate, considerable amount of desorbed Ca^{++} was removed as carbonate leaving the phosphate in solution. Thus the effect of urea upon prolonging the availability of phosphate would be to mix large quantity of urea with phosphate.

The mixing of sulphate salt such as $(NH_4)_2SO_4$ with phosphate showed that the majority of desorbed Ca^{++} was removed from the solution as $CaSO_4$ (Fig. 4). Ammonium sulphate is an acidic fertilizer so that the fraction of $HPO_4^=$ in the phosphate and ammonium sulphate mixture is rather small. Matter of fact less than 1 % of the phosphate is in the form of $HPO_4^=$. Consequently the desorbed Ca^{++} reacted with sulphate and was removed from the solution. Very small amount of phosphate is precipitated as $CaHPO_4$. From the chemical point of view the addition of ammonium sulphate should increase the availability of phosphate in calcareous soil.

CONCLUSION

Theory of phosphate transport in calcareous soil was formulated and presented based on the assumtion that the exchangeable Ca^{++} is mainly responsible for the fixation of the soluble phosphate. The theory is mechanistic in nature and includes all interacting ions and reactions.

The theory which was verified in the laboratory column using ion exchange resin could explain a number of observations. The theory predicts the concentration dependent mobility of phosphate, the effect of soil CEC, and the effect of addition of various salts upon the phosphate mobility and availability to a test crop. It is seen from the theory that the addition of non-reacting salt to phosphatic fertilizer can either reduce or enhance the availability of phosphate. Proper choice of salt appropriate to the soil or external condition can determine the availability of phosphate.

The pattern and position of the phosphate and carbonate precipitates from the point of application of fertilizer can be greatly influenced by the characteristics of fertilizer and local soil conditions.

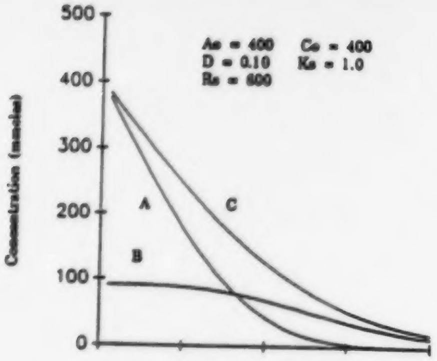


Fig. 1. Distribution of Cation, Ca^{++} and $PO_4^{=}$ without any Chemical reaction.
Time = 33 hrs.

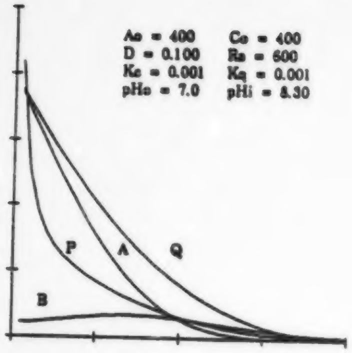


Fig. 2. Distribution of Cation, Ca^{++}, PO, and $CaHPO_4$.
Time = 33 hr.

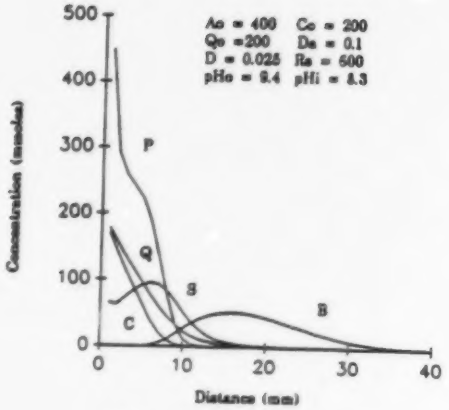


Fig. 3. Distribution of Ca^{++}, $PO_4^{=}$ and $CO_3^{=}$ when Urea was mixed with Phosphate.
Time = 33 hr.

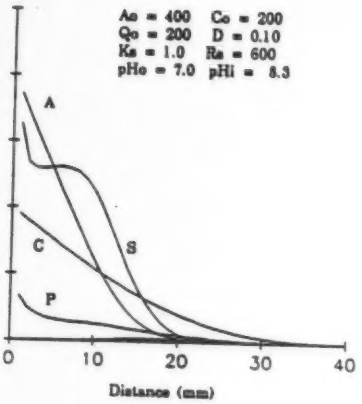


Fig. 4. Effect of Addition of Sulfate Salt upon Phosphate Transport.
Time = 33 hr.

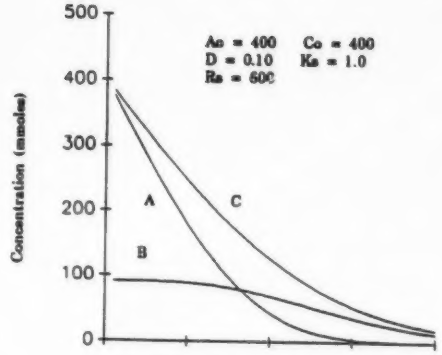


Fig. 1. Distribution of Cation, Ca^{++} and $PO_4^{=}$ without any Chemical reaction.
Time = 33 hrs.

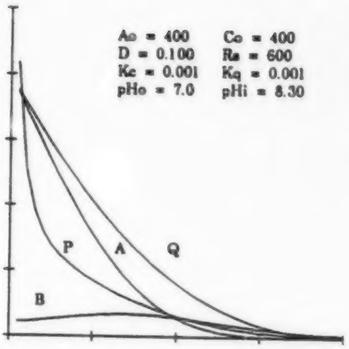


Fig. 2. Distribution of Cation, Ca^{++}, PO_4 and $CaHPO_4$.
Time = 33 hr.

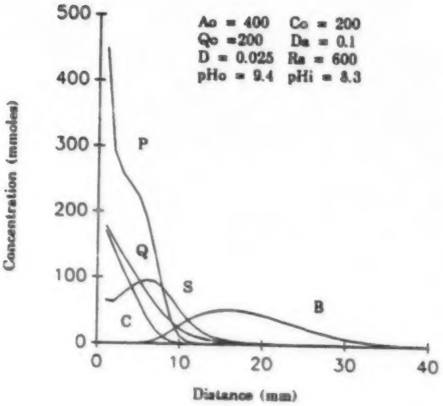


Fig. 3. Distribution of Ca^{++}, $PO_4^{=}$ and $CO_3^{=}$ when Urea was mixed with Phosphate.
Time = 33 hr.

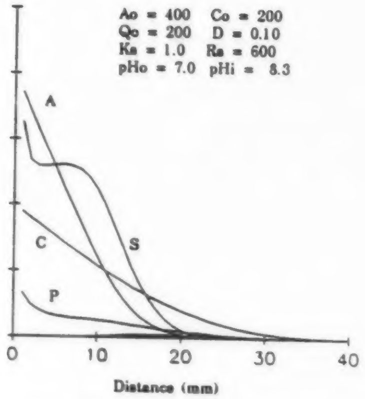


Fig. 4. Effect of Addition of Sulfate Salt upon Phosphate Transport.
Time = 33 hr.

Diffusive Transport and Interaction of P, Ca^{++}, K^+ and H^+ Ions in a Model System

O. O. Akinremi and C. M. Cho
Department Of Soil Science
University of Manitoba

ABSTRACT

This study investigated multi-ionic diffusive transport in a cation exchange resin medium. To ca-saturated resin in a cylindrical wax column was added 0.2 g KH_2PO_4 salt at the surface to simulate a one-dimensional diffusive transport. The ions of interest were Ca^{++}, K^+, H^+ and P ($H_2PO_4^-$ and $HPO_4^=$).

Extraction and analysis of 2mm increments of the wax column after the desired incubation period (3 days, 1 week and 2 weeks) showed that in the absence of cation exchange resin (i.e. exchangeable calcium), both K^+ and P ions travelled at virtually the same speed. No differences were found in the diffusivity of K^+ and P ions in this experiment.

When the cation exchange capacity (CEC) of the resin-sand mixture was increased to 20 meq/100g, Exchangeable Ca^{++} was flushed out by K^+ and accumulated in the soil solution with the highest concentration occurring at 1 cm from the top of the column. Transport of K and P were thus retarded compared to the column with no exchange resin. Increasing the CEC from 20 to 60 meq/100g progressively retarded the movement of K and P ions which then accumulated at the top of the column. More Ca^{++} came into solution as the CEC was increased.

The experimental results shows the effect that the interaction of one ion has on the movement of the other. It also shows the need to take into consideration the interaction of the cation accompanying P (eg K^+) in any model simulating P transport in the soil.

INTRODUCTION

Phosphorus is an important plant nutrient that limits plant productivity under normal agricultural condition. Understanding phosphorus movement and interaction in the soil is fundamental to the understanding of its availability to the plant.

There are three principal mechanisms by which plant nutrients in the soil may reach the surface of a growing root: root interception; mass flow and diffusion. Of these mechanisms the most important for P uptake is diffusion (Barber et al 1963). This is brought about by the low ionic content of P in the soil solution, which makes the contribution via mass flow very small. Hence, the diffusion of P is an important process in the soil.

The diffusive transport of P has been studied in the past either through laboratory experiments (Bouldin and Black 1954, Lewis and Racz 1969) or through the use of mathematical transport models (Bouldin

1961). These studies have in general concentrated solely on the ion of interest - P. Little or no attention was paid to the ion that is associated with the applied P or the ion resident in the soil prior to P application. The possible influence of these ions on the movement and precipitation of P was often not taken into consideration.

It is impossible, however, to apply P to the soil without an added cation in the form of Ca^{++}, K^+, NH_4^+ e.t.c. These cations are known to undergo exchange reaction with the cation residing in the soil. The so-called snow-plow effect (Cho, 1985) results from such interaction. It is not known how such interaction between cations affect the movement of an anionic specie like P.

This study was performed to investigate multi-ionic diffusive transport in a model system of cation exchange resin. We are interested in the transport of K^+, ($H_2PO_4^-$ and $HPO_4^{=}$), Ca^{++} and H^+ in the porous medium. Attention was also paid to the interaction between applied cation K^+ and soil cation Ca^{++} and how this affect the transport of P.

MATERIALS AND METHOD

For studies of this nature the soil is not an ideal system because of the uniqueness of each soil and the complexity of the interaction by ions in the soil system. To overcome this problem we chose a model system of cation exchange resin (Amberlite CG 120). This had a mesh size of 100-200 and a cation exchange capacity (CEC) of 430 meq/100 g. The high C.E.C. made dilution with "inert sand" necessary.

In this system, it is possible to select the type and number of ions and hence, the nature of the interaction. Also, it is possible to modify the CEC. of the system. The resin was washed with water and then leached with 1N $CaCl_2$ solution followed by 0.05 N $CaCl_2$ solution and finally water until the silver nitrate test was negative for chloride. This was to saturate the exchange site with Ca^{++} ion simulating the condition in a calcareous soil where the exchange site is dominated by Ca^{++}. The calcium on the exchange site is henceforth referred to as the soil cation. Inert sea sand were crushed to give materials of mesh size comparable to that of the resin. The resin was then mixed in various proportion with the sand to give a final resin-sand mixture with CEC of 0, 20, 40 and 60 meq/100 g. The zero meq mixture (i.e sand with no resin) was termed the control treatment.

The mixture was packed into a wax column prepared using the method of Khasawneh and Soileau, 1969. The wax column was 10 cm in height with an internal diameter of 4.5 cm. The "soil" was packed to a bulk density of 1.6 g/cc and wetted to a moisture content of 15 %. This was then allowed to equilibrate for 24 hours before the application of a P-salt.

The salt used in all cases was 0.2 g of KH_2PO_4. This was uniformly applied on the surface to simulate a one-dimensional diffusive transport. The columns were then incubated in a desiccator for period of time ranging from 3 day - 2 weeks. All experiments were carried out in duplicate. Main treatments were 0, 20, 40 and 60 meq/100 g of resin-sand mixture. Duplicate columns were then sampled after 3 days, 1 week and 2 weeks of incubation.

After the desired period of incubation the wax columns were sectioned at 2 mm interval using a meat cutter. Samples were then taken simultaneously from each section for moisture content and chemical analysis. Approximately 1 g of the resin-sand mixture in each section was weighed into a centrifuge tube. One ml of water was applied and the pH of the mixture was measured. Nine mls of water was then added for extraction at a soil to solution ratio of 1:10. This was termed "the water extractable fraction". This was followed by 2 successive extractions with 10 ml of 1N HCl which was termed "the acid extractable fraction".

The water extractable fraction approximates what is in soil solution i.e the mobile phase, while the acid extractable fraction approximates what is on the solid i.e. the immobile phase. The data presented relates to the water extractable fraction only.

The pH of the "soil" was determined using the glass electrode. The water extractable P was determined by the Ascorbic acid method. Water extractable K^+ and Ca^{++} was determined using the Atomic Absorption Spectrophotometer.

RESULTS AND DISCUSSION

Ionic profile in the control column

The soil pH

The zero meq sand is an unbuffered system, hence, it assumed the pH imposed on it by the salt. The pH of the column as a function of time is shown in Fig 1a. The highest H^+ ion concentration occurred on the top of the column which is expected because of the presence of applied salt. As the hydrogen ion diffused down the column it depressed the pH of the system below that of the background which in this case was about pH 7.

With time, however, there was a rise in pH at the top of the column as the hydrogen ion diffused further into the column signifying a decrease in concentration of H^+ ion at the top of the column with time. Down the column, there is a concomitant decline in pH as more and more H^+ ions moved from the top to the bottom of the column.

The soil P and K

The phosphorus profile in the zero meq sand columns followed the pattern expected for a diffusion controlled process (Fig. 1b). Here we assumed that the phosphate ions were involved in no interaction either in the form of precipitate formation or adsorption. The movement of P in the system was, thus, fairly rapid as a result of the lack of retardation. After 3 days of incubation, P had moved to a distance of 4 cm, after 1 week it had moved 6 cm down the column and up to 9 cm after 2 weeks of incubation. As a function of incubation time, then, the P concentration at the upper 2 cm portion of the column declined with a concomitant rise in P level below this portion of the column. This signifies mobility of the phosphate ion down the column. Because of the lack of interaction the area under each curve should be the same for conservation of mass.

The K^+ ion behaved in a similar manner to that of the phosphate ion as shown in Figs 1c and 1d. Figure 1d is a comparison of the concentration profile of the two ions when there was no interaction. As shown in Fig 1d K^+ ion and phosphate ion have identical concentration profile after 3 days and 1 week of incubation. Hence, there was no difference in the diffusion rate of these ions in this experiment. This is expected, however, since there was no interaction between the ions in the system. The water extractable Ca^{++} in this sand column was negligible. Since no Ca^{++} saturated resin was added, this result is expected. The absence of Ca^{++} in the system made our assumption of no retardation justifiable.

Ionic profile in the 60 meq column

The ionic distribution in a column packed with 60 meq/100g soil is shown on Fig 2 (a, b, c, d) as a function of incubation time. The shape of the pH curve (Fig 2a) followed that of the control (Fig. 1a). The main difference was that in this system the pH at the top portion of the column was lower than in the control. This reduction in pH signified higher H^+ ion concentration at the top of the column. This was probably due to the production of H^+ ion as a result of the reaction between Ca^{++} and $HPO_4^{=}$ species to form DCPD precipitate. This reaction disturbed the equilibrium shown below:

$$H_2PO_4^- = HPO_4^= + H$$

causing a shift to the right, hence, an increase in H^+ concentration.

The Ca^{++} ion concentration in the 60 meq resin is shown in Figure 2b. We assumed that initially the concentration of Ca^{++} in soil solution was zero since the Ca^{++} ions were on the exchange site. The K^+ ion as it diffused down the column kicked out Ca^{++} ion from the exchange site resulting in the accumulation and diffusion of Ca^{++} down the column. This Ca^{++} formerly on the exchange site was rendered available for precipitation reaction with the phosphate ion. The build-up of Ca^{++} ion in solution following the application of K^+ ion is what has been described as the snow-plow effect. This data is thus important since it validates the known theory of cation exchange process in the soil. The exchange reaction is indicated below:

$$\text{Ca-Resin} + 2K^+ = K_2\text{-Resin} + Ca^{++}$$

The generally low pH of the unbuffered system allowed the accumulation of Ca^{++} by reducing the level of precipitation. In the soil the pH would be buffered, hence, enough species of $HPO_4^=$ will be available to prevent the accumulation of Ca^{++} ion in the soil. It may thus, be difficult to detect the snow-plow effect in the natural soil. With time, the calcium level declined as a result of removal from solution by P in the form of precipitation and also diffusion down the column.

The K ion distribution along the column is shown in Fig 2c and the pattern is also similar to that of the control Fig. 1c. The main difference is the rate of movement of K ion as indicated by the distance of travel after a given period of time. We see that the K ion is retarded in the 60 meq resin when its movement is compared to that in the control. After 3 days it has moved 1.5 cm down the column, 2.2 cm down the column after 1 week and 3.2 cm after 2 weeks. This can be compared to 4 cm, 7 cm and more than 9 cm after 3 days, 1 week and 2 weeks, respectively, in the control column where there was no interaction. The retardation of K was due to its interaction with exchangeable Ca^{++}.

P profile in the 60 meq resin is shown in Figure 2d. The pattern is similar to that of K^+. The movement of P too is retarded in the 60 meq resin-sand mixture compared to that in the control (Fig 2d and 1c). The retardation of P is due to its precipitation reaction with the Ca^{++} liberated from the exchange site by K^+. The divalent phosphate ion reacted with the calcium ion to form a precipitate, which is probably DCPD.

Effect of CEC on ion transport

The effect of increasing CEC of the system on the ionic transport is shown in Figure 3 (a, b, c and d). For H^+ ion, the higher the CEC the higher was the H^+ concentration at the top of the column (Fig 3a). This was due to the higher magnitude of P precipitation with increasing solution Ca^{++} (Fig 3b) causing the production of H^+.

For the Ca^{++} ion, solution Ca^{++} increased with the CEC of the mixture (Fig. 3b). This makes sense since Ca was the cation on the exchange site, increased CEC implied increased Ca^{++} ion in the system. The more the exchangeable Ca^{++} encountered by K^+ the more was the Ca^{++} ion liberated into the soil solution. Although the same amount of KH_2PO_4 was applied in all situations more Ca^{++} was liberated the higher the CEC.

For K^+. the retardation of this ion by in creasing C.E.C is clearly shown in Figure 3c which is the data generated after 1 week of incubation. The implication of this is that in soils of different CEC the movement of potassium can not be assumed to be the same. Method of application of potassium fertilizer or the amount applied has to take this into consideration.

An important finding in this study was that the interaction between cations in the form of exchange reaction did affect the movement of the anionic specie - phosphorus. Figure 3d shows that as the CEC was increased from zero to 60 meq the distance travelled by P declined from 7 to 3 cm after 1 week of incubation. The reason for this is the increased level of Ca^{++} liberated into the soil solution by K^+ which were then made available for P precipitation.

Looking at Fig. 3c and 3d we see that the magnitude of K retardation as a result of increasing C.E.C. is slightly greater than that of the phosphate ion. This is due to the stoichiometry of the interaction. It takes two K^+ ion to liberated one Ca^{++} ion, but only one phosphate ion reacts with one calcium ion. Thus, on a mole basis 2 moles of K^+ disappeared from solution for every mole of P that is precipitated. The overall effect is that K is more retarded than P.

SUMMARY AND CONCLUSION

In this model system the following points are apparent: When there was no interaction both K and P ions behaved in a similar manner with regards to their diffusive transport. Exchange reaction between applied K^+ and soil Ca^{++} caused the build up of Ca^{++} in the soil solution. The higher the CEC of the system the more was the Ca^{++} liberated. Cation exchange retarded the movement of both K and P, the higher the CEC the higher was the degree of retardation.

REFERENCES

Bouldin, D. R. 1961. Mathematical description of diffusion processes in the soil-plant system. Soil Sci. Soc. Am. Proc. 25:476-480

Bouldin, D. R., and Black, C. A. 1954. Phosphorus diffusion in soils. Soil Sci. Soc. Am. Proc. 18:235-259

Barber, S. A., Walker, J. M., and Vasey, E. H. 1963. Mechanisms for the movement of plant nutrients from the soil and fertilizer to the plant root. J. Agric. Food Chem. 11: 204-207.

Cho, C. M. 1985. Ionic transport in soil with ion-exchange reaction. Soil Sci. Soc. Am. Proc. 49:1379-1386.

Khasawneh, F. E., and Soileau, J. M. 1969. Soil preparation and sampling for studying ion movement. Soil Sci, Soc. Am. Proc. 33:476-477.

Lewis, E. T., and Racz, G. J. 1969. Phosphorus movement in some calcareous and noncalcareous Manitoba soils. Can. J. Soil Sci. 49:305-312.

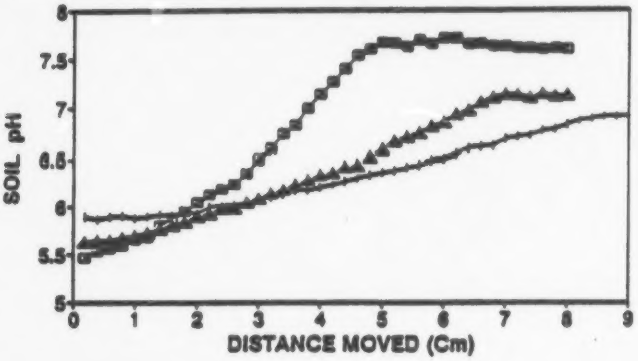


Fig. 1a

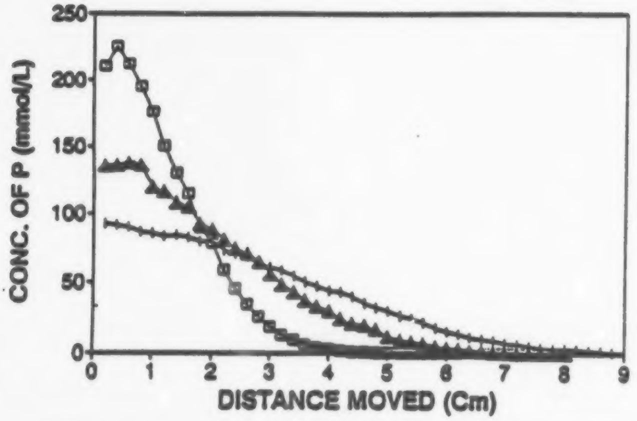


Fig. 1b

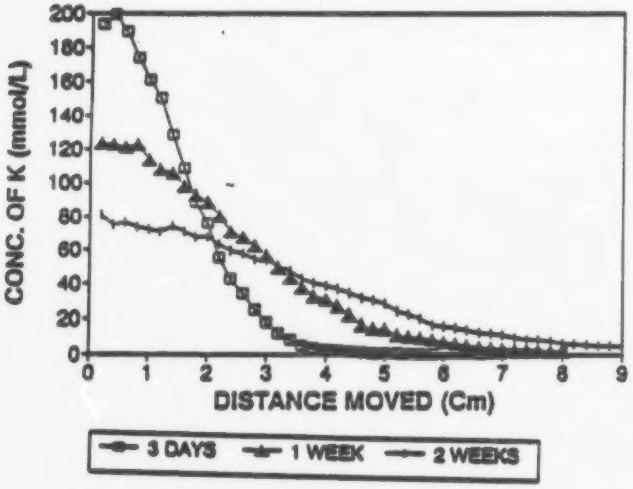


Fig. 1c

Figures 1a, 1b and 1c. The pH, phosphorus and potassium profile in the control column with time.

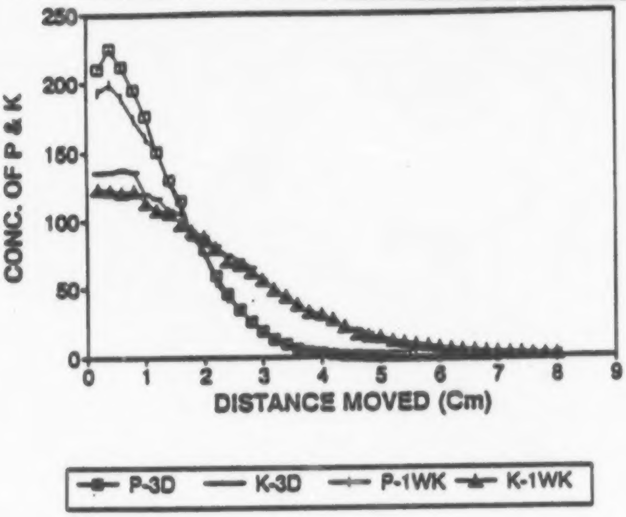


Figure 1d. Comparative levels of K and P in the control column.

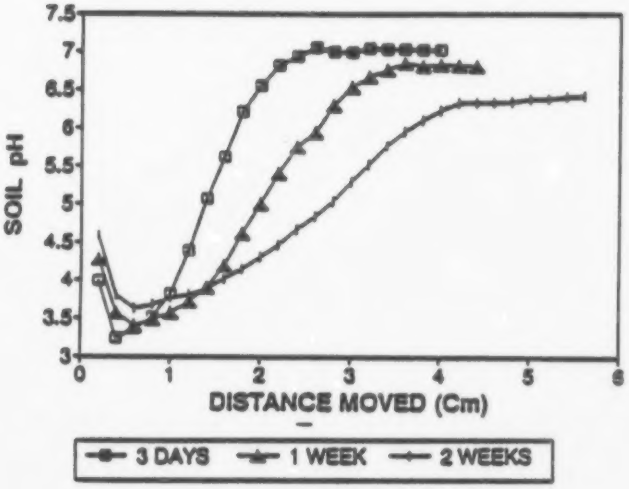


Figure 2a. The pH of 60 meq resin-sand column with time.

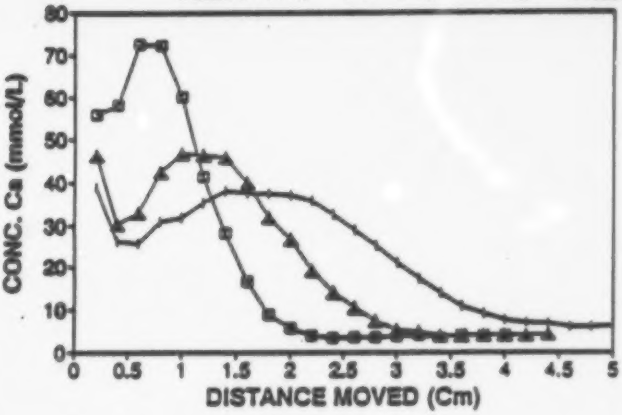


Fig. 2b.

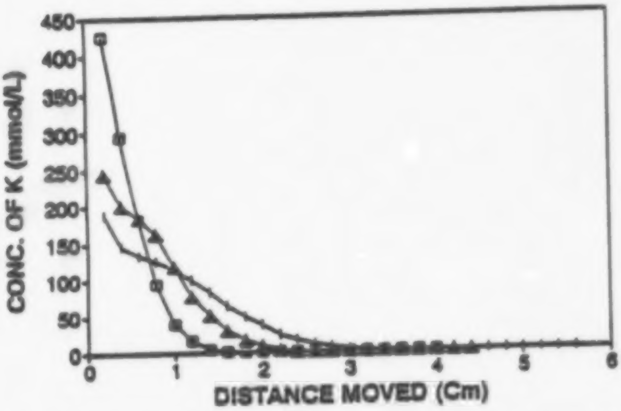


Fig. 2c.

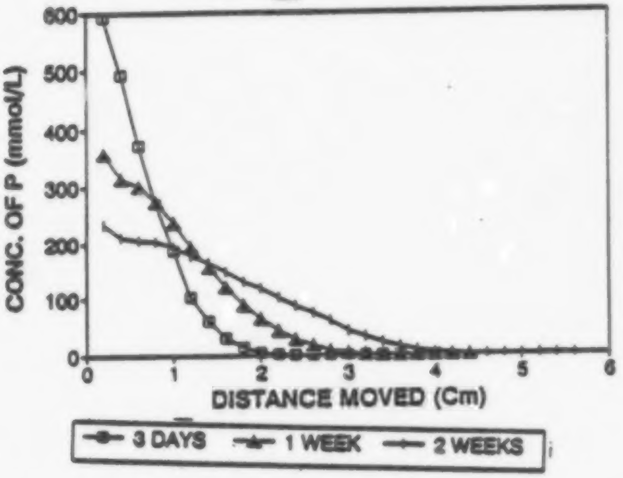


Fig. 2d.

Figures 2b, 2c and 2d. The calcium, potassium and phosphorus levels in the 60 meq resin-sand column with time.

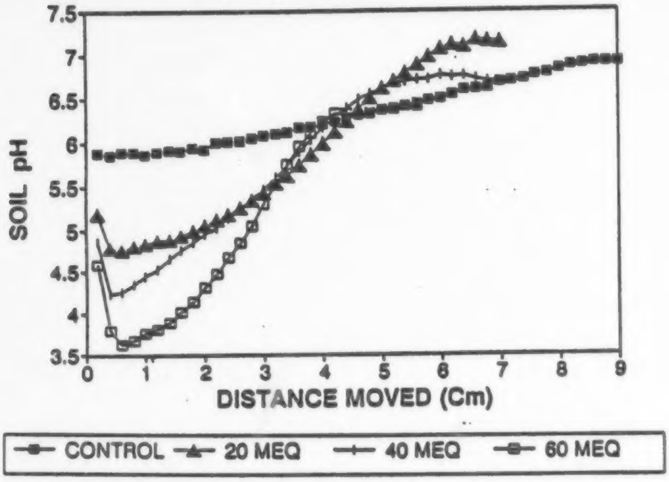


Fig. 3a.

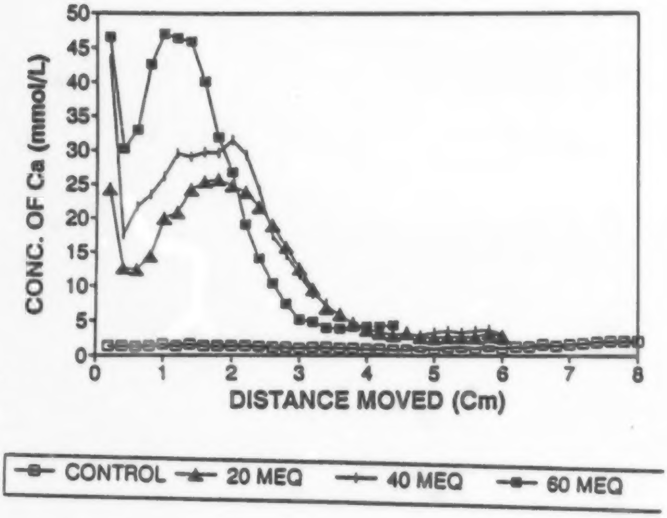


Fig. 3b.

Figures 3a and 3b. Effect of CEC on pH and calcium distribution along the resin-sand column.

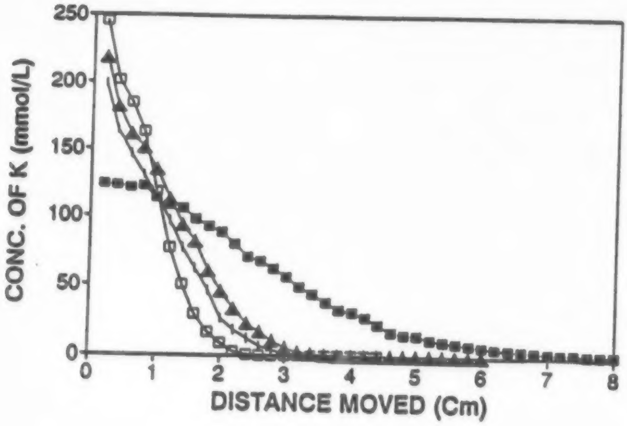


Fig. 3c.

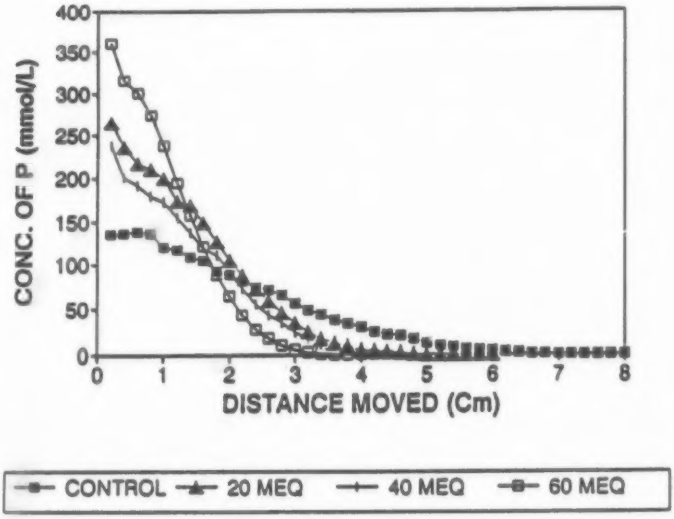


Fig. 3d.

Figures 3c and 3d. Effect of CEC on K and P profile in resin-sand column.

The Effect of PB-50 (Penicillium bilaji Inoculant) on Yield and Phosphorus Uptake by Wheat

J. W. Chambers and J. C. Yeomans, University of Manitoba

ABSTRACT

Field and growth chamber experiments were conducted, growing wheat, to determine the effect of PB-50 (Penicillium bilaji inoculant) on dry matter yield and plant uptake of phosphorus (P). In growth chamber experiments, using ^{32}P, yields were higher with the PB-50 treatment at each rate of P applied, but these increases were not statistically significant. Similar results were observed for total P uptake: P uptake was increased with the PB-50 treatment at each fertilizer rate, but the increase was not statistically significant. At the higher rates of P fertilizer however, a larger fraction of the total plant P was obtained from the soil P pool, in those plants which had been treated with PB-50. The field experiments were conducted at three sites in southern Manitoba. The results for the yield data were similar to results obtained in the growth chamber experiment. Yields were always higher for the treatments that included PB-50, but at only one site, and at one P rate, was the increase in yield statistically significant. Plant samples were taken through the growing season to measure P uptake. In most cases, the PB-50 seed treatment enhanced P uptake by the plant, and this was generally statistically significant at the early stages of growth.

INTRODUCTION

The soil contains a limited amount of plant available phosphorus (P), less than 1% of the total soil P being in the soil solution. Therefore, plant growth can be enhanced with the application of P fertilizers (Ozanne, 1980). However, although P fertilizer is initially available for plant uptake, it will readily react with the soil, rendering a large percentage, up to 90%, unavailable to the plant (Stevenson, 1986). These insoluble 'fixed' P forms, orthophosphate, and calcium, iron, and aluminum minerals, can have some residual benefits, if exploited properly (Barber, 1984). For example, there is evidence that organic acids may accumulate in localized zones in the soil in sufficient quantities to appreciably increase the availability of these insoluble phosphates to plants (Stevenson, 1967).

Research during the past 40 years has indicated that rhizosphere microorganisms will affect the plant availability of phosphates, likely through the production of organic acids. Gerretsen (1948) is usually credited as the first to draw attention to the influence of rhizosphere microorganisms on phosphate uptake by plants, and numerous researchers since have reported evidence of phosphate solubilizing microorganisms in soil and in particular, in the rhizoplane and rhizosphere of various crops (Katznelson et al., 1962; Taha et al., 1969; Banik and Dey, 1982; Kucey, 1983; Venkateswarlu et al., 1984). The most frequently isolated organisms that solubilize phosphates are genera of bacteria and fungi, and evaluation of cultures have indicated that the fungi are more efficient than bacteria in phosphate solubilization (Kucey, 1983; Venkateswarlu et al., 1984). Also, fungi retain this ability over many subculturing transfers whereas a high percentage of bacterial isolates lose their solubilizing ability when subcultured (Kucey, 1983).

Considerable work has been reported on the effectiveness of Penicillium spp., particularly Penicillium bilaji, for solubilizing phosphates in soil. Under greenhouse and field conditions, the addition of P. bilaji, with or without added rock phosphate, resulted in increases in plant dry matter production and P uptake in wheat, field beans, and canola (Kucey, 1987; Asea et al., 1988; Kucey, 1988; Kucey and Leggett, 1989).

PhilomBios has developed an agricultural product, PB-50, using the fungi P. bilaji, that has been extensively researched in Alberta and Saskatchewan. The PB-50 can be used either as a seed treatment or as an in-furrow granular form. Work is currently being conducted in western Canada on various crops including barley, beans, canola, corn, peas, soybeans, and wheat, to test the effectiveness of this inoculant for increasing P availability to the plant.

The objective of this research was to determine if the fungal seed coating, PB-50, would enhance P uptake and plant yield of wheat, grown in growth chamber and field experiments. In the growth chamber, the ^{32}P-labelled fertilizer was applied to determine the contribution of fertilizer and soil P on total P uptake by plants. In the field experiments, plant samples were harvested throughout the growing season to determine time of initiation of P uptake by the wheat.

MATERIALS AND METHODS

The soil used in the growth chamber experiment was a surface (0-15 cm) sample of an Almasippi very fine sandy loam from Haywood, MB. The soil contained 3.0 μg g^{-1} NaHCO$_3$-ext P and had a pH of 8.1. Before use, the soil was air dried and sieved (<2 mm).

Wheat (Triticum aestivum cv. Columbus) was grown in the soil treated with four rates of ^{32}P-labelled phosphorus fertilizer: 0.0, 2.5, 5.0, and 10.0 μg P g^{-1} soil labelled with 0, 370, 740, and 1480 kBq, respectively, and with and without a fungal seed coating. The experiment was arranged in a completely randomized design with three replications.

Wheat seeds were coated with P. bilaji inoculant, PB-50 (obtained from PhilomBios Biotechnological Products, Saskatoon, SA). The coating was prepared by suspending 1 g of PB-50 in 30 mL of deionized water. The 30 mL suspension was pipetted over 1 kg of wheat seed in a polyethylene bag and shaken to obtain an even coating. The treated seed was allowed to dry before planting. The PB-50 suspension and samples of the coated seed were analyzed by PhilomBios for fungal viability (Table 1).

Samples of soil (5 kg) were evenly treated with 100 μg N g^{-1} soil as NH$_4$NO$_3$, and 100 μg K g^{-1} soil and 40 μg S g^{-1} soil as K$_2$SO$_4$. Then, 3.7 kg of the treated soil was placed into 6 kg pots (20-cm diameter) lined with polyethylene bags and a solution of ^{32}P-labelled P fertilizer was applied in a 15-cm band in the centre of the pot. An additional 1.5-cm layer (650 g soil)

Table 1. Spore counts of PB-50 suspension and coated wheat seeds.

Site	PB-50 Suspension (cfu g^{-1})	Coated seed (cfu $seed^{-1}$)
Growth chamber		
Almasippi VFSL	2.1×10^9	1.94×10^4
Field experiments		
Wellwood SCL	7.2×10^8	2.23×10^5
Stockton FSL	6.0×10^8	1.47×10^4
Portage SiC	7.2×10^8	2.23×10^5

of treated soil was lightly packed on top of the fertilized soil and twelve wheat seeds were placed in a straight row directly above the labelled-P band. The remaining nutrient soil (approximately 1.5 cm) was placed on top of the seed, lightly packed, and moistened to 2/3 field capacity with distilled water. The pots were maintained at 2/3 field capacity (by weight) by adding distilled water to the soil surface daily.

The pots were thinned to 6 plants per pot seven days after emergence, and were side dressed with 100 μg N g^{-1} soil (as NH_4NO_3) four weeks after planting. After 8 weeks of growth (heading stage) the plants were harvested, oven dried for 4 days at 65°C, weighed (for dry matter yields) and ground. Samples of the ground tissue were analyzed for ^{32}P with a Beckman scintillation counter using the 'H#' technique (Wang et al., 1975). The samples were also analyzed for ^{31}P (Isaac and Kerber, 1971).

The results of the experiment were statistically analyzed using the GLM procedure (Goodnight et al., 1988).

In the field experiments, wheat (T. aestivum cv. Katepwa) was grown at three sites in southern Manitoba: two sites at Carberry (Wellwood SCL, pH=5.7, $NaHCO_3$-ext P=11.8 and Stockton FSL, pH=6.6, $NaHCO_3$-ext P=11.9) and one site at Portage (Portage SiC, pH=8.1, $NaHCO_3$-ext P=3.8). The experiments at each site were arranged in a split plot completely randomized design (Little and Hills, 1978) with five P_2O_5 rates (0, 5, 10, 20, and 40 kg ha^{-1}) as the treatments, and with and without a fungal seed coating of PB-50 as the subtreatments. The seed preparation and spore counts (Table 1) for the PB-50 were as described in the growth chamber experiment.

Basal treatments of N and K were broadcast at each field site, according to soil test recommendations, using a Valmar air-flow granular applicator, incorporated to a depth of 8 cm with a tandem disc, and cross worked with diamond toothed harrows. Wheat was seeded to a 2.5-cm depth (90 kg ha^{-1} with 15-cm row spacing) using a double disc press. Phosphorus fertilizer, as monoammonium phosphate (MAP), was banded near the seed. Early season weed control was maintained through recommended applications of Hoegrass.

Plant samples were taken from all plots, on an area basis, at 7, 14, 28, and 56 days after emergence, and at plant maturity. The plant samples were oven dried (65°C), weighed, ground (for dry matter yields), and analyzed for ^{31}P (Isaac and Kerber, 1971).

The results of the experiment were statistically analyzed using the GLM procedure (Goodnight et al., 1988).

RESULTS AND DISCUSSION

In the growth chamber experiment, the PB-50 treatment increased the dry matter yields of wheat, as compared to the non-inoculated plants. However, the increases in yield were not statistically significant (Table 2).

Table 2. Effect of phosphorus fertilizer and PB-50 on yield of wheat.

Fertilizer P added	Yield	
	No PB-50 added	PB-50 added
– kg ha^{-1} –	g pot^{-1}	
0	12.8 a[†]	15.0 ab
5	18.7 bc	21.0 cd
10	21.4 cd	22.4 cde
20	24.7 de	26.7 e

[†] Numbers followed by the same letter are not significantly different at 0.05 level and apply only to comparisons for treatments with and without PB-50.

The PB-50 treatment also enhanced total P uptake at all P fertilizer rates, as compared to the non-treated plants, but again the increases were not significant (Table 3). However, the use of ^{32}P made it possible to determine the contribution of fertilizer and soil P to the total P uptake by the wheat plants (Table 3). At 5 and 10 kg P ha^{-1}, the PB-50 treatment enhanced the fertilizer P uptake, and at 10 kg P ha^{-1} the difference was statistically significant. At 20 kg P ha^{-1}, fertilizer P uptake was significantly inhibited by the PB-50 treatment.

The P obtained from the soil contributed the remainder of plant P. Plants grown with the PB-50 treatment, at all P fertilizer rates, showed increased soil P uptake as compared to the plants grown without the PB-50 treatment. The

Table 3. Effect of phosphorus fertilizer and PB-50 on phosphorus uptake by wheat.

Fertilizer P added	PB-50	Phosphorus uptake		
		Soil	Fertilizer	Total
– kg ha^{-1} –		mg pot^{-1}		
0	-	14.8 ab[†]	0.0 a	14.8 a
0	+	20.2 b	0.0 a	20.2 ab
5	-	19.1 bc	4.4 b	23.5 bc
5	+	24.4 c	5.1 b	29.5 cd
10	-	15.3 ad	8.7 c	24.0 bcd
10	+	21.4 bc	10.5 d	31.9 de
20	-	9.4 a	18.8 f	28.2 cd
20	+	23.8 c	16.0 e	39.8 de

[†] Numbers for each phosphorus form followed by the same letter are not significantly different at 0.05 level and apply only to comparisons for treatments with and without PB-50.

increases were significant at the 10 and 20 kg P ha^{-1} fertilizer treatments. Similar results were obtained by Asea et al. (1988). They reported that inoculation with P. bilaji resulted in ^{32}P isotopic dilution due to release of P from the native soil P.

It is interesting that the plants inoculated with PB-50 had a constant soil P uptake with additional increases in P fertilizer, compared to decreases in soil P uptake with additional increases in P fertilizer without the PB-50 treatment (Table 3).

Similar results were obtained in the field experiments, where the PB-50 treatment enhanced the dry matter yields of wheat at all P fertilizer rates and at each of the three sites, as compared to the noninoculated plants (Table 4). At the early stages of growth, these dry matter yields for the inoculated treatments were significantly higher than the noninoculated treatments. However, at the later sampling stages, although there were apparent yield increases with the inoculated treatments, the increases were not significant (Table 4).

The grain yields of the PB-50 treated wheat plants were also higher than the noninoculated plants, at most of P fertilizer rates and at each of the three sites (Table 5). However, only at one Carberry site on the Wellwood soil, at the fertilizer rate of 20 kg P_2O_5 ha^{-1} with the PB-50 treatment, was the increase statistically significant as compared to the noninoculated treatment.

Table 4. Effect of P fertilizer and PB-50 on total dry matter yield at various growth stages.

Fertilizer P_2O_5 added	PB-50	Dry Matter				
		Week 1	Week 2	Week 4	Week 8	Maturity
— kg ha^{-1} —		g m^{-2}				
				Wellwood Soil		
0	-	2.02	5.59	41.84	397.8	504.8
0	+	2.26	7.77	44.56	487.5	539.6
5	-	1.96	5.87	35.72	448.5	521.0
5	+	2.58	7.42	43.99	547.3	586.2
10	-	1.88	5.84	44.38	432.9	429.0
10	+	2.71	7.36	59.23	436.8	473.4
20	-	1.81	6.23	39.67	436.8	411.6
20	+	2.74	7.96	62.92	569.4	574.6
40	-	2.15	7.29	52.96	496.6	540.4
40	+	2.81	7.68	56.55	549.9	566.4
LSD (P=0.05)[†]		0.59	1.51	12.20	168.8	160.7
				Stockton Soil		
0	-	1.58	5.31	18.51	416.0	597.4
0	+	2.19	5.57	27.68	430.3	612.4
5	-	1.79	5.11	26.69	399.1	487.6
5	+	2.58	6.70	30.74	418.6	590.4
10	-	1.38	5.13	26.34	409.5	580.4
10	+	2.13	6.29	36.71	503.1	599.0
20	-	2.04	5.78	32.84	395.2	653.0
20	+	2.26	6.67	41.48	482.3	662.8
40	-	1.92	5.89	36.00	445.9	614.6
40	+	2.70	7.03	48.74	603.2	666.2
LSD (P=0.05)		0.48	0.79	9.98	149.7	159.4
				Portage Soil		
0	-	1.71	4.23	33.38	495.3	754.8
0	+	1.74	5.74	40.77	678.6	795.8
5	-	1.76	4.71	33.26	510.9	867.6
5	+	1.96	5.90	36.62	611.0	894.2
10	-	1.66	4.59	29.65	605.8	850.0
10	+	2.24	6.12	40.14	612.3	989.2
20	-	1.78	5.23	36.06	560.3	855.8
20	+	2.13	6.99	45.51	682.5	882.2
40	-	1.60	5.37	40.95	529.1	875.4
40	+	2.37	6.81	54.81	608.4	996.2
LSD (P=0.05)		0.40	0.91	11.06	244.9	197.2

[†] LSD values apply only to comparisons of means for treatments with and without PB-50.

Table 5. Effect of P fertilizer and PB-50 on grain yield of wheat.

Fertilizer P_2O_5 added	Grain Yield	
	No PB-50 added	PB-50 added
--- kg ha^{-1} ---	kg ha^{-1}	kg ha^{-1}
	Wellwood	
0	2345	2526
5	2381	2687
10	1828	2215
20	1897	2668
40	2397	2620
LSD (0.05)†	750	
	Stockton	
0	2784	2804
5	2283	2663
10	2352	2418
20	2930	2963
40	2616	2800
LSD (0.05)	684	
	Portage	
0	3538	3658
5	4054	3990
10	3900	4504
20	4080	4146
40	3918	4672
LSD (0.05)	887	

† LSD values apply only to comparisons of means for treatments with and without PB-50.

The total P uptake was enhanced by the PB-50 treatment at most P fertilizer rates and at all three sites (Table 6). At the early growth stages, significant increases in P uptake, with the PB-50 treatment, were manifested in a significant increase in dry matter yield (Tables 4 and 6). Although there were significant increases in P uptake at maturity, at all three sites, with the PB-50 treatment as compared to noninoculated treatments, this did not result in corresponding significant increases in yield.

It is noteworthy that at the Carberry site on the Wellwood soil, the PB-50 treatment at the fertilizer rate of 20 kg P_2O_5 ha^{-1}, showed significant increases

Table 6. Effect of P fertilizer and PB-50 on total P uptake at various growth stages.

Fertilizer P_2O_5 added	PB-50	Total P uptake				
		Week 1	Week 2	Week 4	Week 8	Maturity
— kg ha^{-1} —		mg plant^{-1}				
				Wellwood Soil		
0	-	0.071	0.154	1.471	6.490	8.139
0	+	0.081	0.216	1.476	8.026	7.899
5	-	0.074	0.174	1.237	7.788	7.705
5	+	0.093	0.230	1.493	9.284	8.489
10	-	0.071	0.173	1.623	7.148	5.950
10	+	0.099	0.214	2.021	6.883	7.435
20	-	0.074	0.212	1.543	7.370	5.866
20	+	0.110	0.247	2.214	9.719	9.034
40	-	0.103	0.257	2.023	7.010	7.057
40	+	0.141	0.269	2.073	9.217	8.375
LSD ($P=0.05$)[†]		0.025	0.055	0.429	3.491	2.401
				Stockton Soil		
0	-	0.046	0.099	0.718	5.822	7.686
0	+	0.064	0.104	0.834	7.142	8.745
5	-	0.049	0.103	0.814	5.991	6.788
5	+	0.073	0.132	0.965	6.099	8.885
10	-	0.054	0.124	0.851	6.418	6.660
10	+	0.066	0.129	1.147	8.320	8.310
20	-	0.065	0.151	1.104	6.132	8.102
20	+	0.068	0.160	1.424	7.173	9.196
40	-	0.069	0.181	1.186	6.429	6.584
40	+	0.093	0.214	1.728	9.313	9.185
LSD ($P=0.05$)		0.011	0.029	0.318	2.555	2.030
				Portage Soil		
0	-	0.057	0.134	0.930	7.394	11.040
0	+	0.066	0.198	1.193	10.190	11.277
5	-	0.059	0.150	0.978	7.716	11.125
5	+	0.064	0.193	1.047	9.879	12.575
10	-	0.049	0.153	0.825	9.191	11.050
10	+	0.077	0.223	1.188	8.513	15.111
20	-	0.067	0.195	1.141	8.478	11.814
20	+	0.080	0.269	1.406	11.239	13.649
40	-	0.068	0.218	1.297	8.668	10.660
40	+	0.104	0.280	1.812	9.769	15.415
LSD ($P=0.05$)		0.015	0.047	0.401	4.010	3.402

[†] LSD values apply only to comparisons of means for treatments with and without PB-50.

in dry matter yield, grain yield and total P uptake, as compared to the fertilizer rate of 20 kg P_2O_5 ha^{-1} that did not receive the PB-50 treatment. Also at the Carberry site, but on the Stockton soil, the PB-50 treatment at the fertilizer rate of 40 kg P_2O_5 ha^{-1}, had significant increases in total P uptake at every growth stage sampled, as compared to the same fertilizer rate that did not receive the PB-50 treatment (Table 6). And, at each growth stage except maturity, this increase in total P uptake had a corresponding significant increase in yield (Table 4).

CONCLUSIONS

We found that the fungal seed coating PB-50, will enhance P uptake and plant yield of wheat. These increases were significant, as compared to noninoculated plants, at the early stages of growth but not significant, in most cases, at maturity. Using ^{32}P-labelled fertilizer, we found that the plants grown with the PB-50 treatment, at all P fertilizer rates, showed increased soil P uptake as compared to the plants grown without the PB-50 treatment. In the field experiment, it appears that the total P uptake by the plant is increased with the PB-50 treatment, showing significantly higher total P in the plants at earlier growth stages. However, this increased total P uptake with the PB-50 treatment, at the early growth stages, did not show a corresponding significant increase in yield at final harvest.

This research was supported in part by the Natural Sciences and Engineering Research Council of Canada, by Elanco Division of Eli Lilly Canada, and by PhilomBios, Biotechnological Products, Saskatoon, SA.

REFERENCES

Asea, P. E. A., R. M. N. Kucey, and J. W. B. Stewart. 1988. Inorganic phosphate solubilization by two Penicillium species in solution culture and soil. Soil Biology & Biochemistry 20:459-464.

Banik, S., and B. K. Dey. 1982. Available phosphate content of an alluvial soil as influenced by inoculation of some isolated phosphate-solubilizing microorganisms. Plant and Soil 69:353-364.

Barber, S. A. 1984. Soil Nutrient Bioavailability. John Wiley & Sons, New York.

Gerretsen, F. C. 1948. The influence of microorganisms on the phosphate intake by the plant. Plant and Soil 1:51-81.

Goodnight, J. H., J. P. Sall, W. S. Sarle, R. D. Tobias, and Y. C. Yuan. 1988. The GLM procedure. In SAS User's Guide: Statistics. pp. 549-640. SAS Institute Inc., Cary, NC.

Isaac, R. A., and J. D. Kerber. 1971. Atomic absorption and flame photometry: Techniques and uses in soil, plant, and water analysis. In Instrumental Methods for Analysis of Soils and Plant Tissue (L. M. Walsh, Ed.). pp. 17-37. Soil Science Society of America, Madison, WI.

Katznelson, H., E. A. Peterson, and J. W. Rovatt. 1962. Phosphate-dissolving microorganisms on seed and in the root zone of plants. Canadian Journal of Botany 40:1181-1186.

Kucey, R. M. N. 1983. Phosphate-solubilizing bacteria and fungi on various cultivated and virgin Alberta soils. Canadian Journal of Soil Science 63:671-678.

Kucey, R. M. N. 1987. Increased phosphorous uptake by wheat and field beans inoculated with a phosphorous-solubilizing Penicillium bilaji strain and with vesicular-arbuscular mycorrhizal fungi. Applied and Environmental Microbiology 53:2699-2703.

Kucey, R. M. N. 1988. Effect of Penicillium bilaji on the solubility and uptake of P and micronutrients from soil by wheat. Canadian Journal of Soil Science 68:261-270.

Kucey, R. M. N., and M. E. Leggett. 1989. Increased yields and phosphorous uptake by Westar canola (Brassica napus L.) inoculated with a phosphate-solubilizing isolate of Penicillium bilaji. Canadian Journal of Soil Science 69:425-432.

Little, T. M., and F. J. Hills. 1978. Agricultural Experimentation, Design and Analysis. John Wiley & Sons, New York.

Ozanne, P. G. 1980. Phosphate nutrition of plants - A general treatise. In The Role of Phosphorous in Agriculture. (F. E. Khasawneh et al., Eds.). pp. 559-589. American Society of Agronomy, Madison, WI.

Stevenson, F. J. 1967. Organic acids in soil. In Soil Biochemistry, Vol. 1 (A. D. McLaren and G. H. Peterson, Eds.). pp. 119-146. Marcel Dekker, New York.

Stevenson, F. J. 1986. Cycles of Soil. Carbon, Nitrogen, Phosphorous, Sulfur, Micronutrients. John Wiley & Sons, New York.

Taha, S. M., S. A. Z. Mahmoud, A. H. El-Damaty, and A. M. A. El-Hafez. 1969. Activity of phosphate-dissolving bacteria in Egyptian soils. Plant and Soil 31:149-160.

Venkateswarlu, B., A. V. Rao., and P. Raina. 1984. Evaluation of phosphorous solubilization by microorganisms isolated from Aridisols. Journal of the Indian Society of Soil Science 32:273-277.

Wang, C. H., D. L. Willis, and W. D. Loveland. 1975. Radictracer Methodology in the Biological, Environmental, and Physical Sciences. Prentice-Hall, Inc., New Jersey.

The effect of N & P and the inoculation with *Rhizobium* and VA-Mycorrhiza on lentil growth and N_2 fixation

John Gehrer and R.J. Soper
Department of Soil Science
University of Manitoba, R3T 2N2

INTRODUCTION

Lentil, a high protein seed crop used primarily for human consumption is part of the leguminosae family, and is grown in Western Canada. In 1980 the worldwide average seed yield of lentil was 655 kg•ha^{-1} (Witcombe and Erskine; 1984). Little research has been conducted and only a few improved varieties exist. However, there is great variability within the existing germplasm collection, thus by selecting superior yielding plants from a seedrow, yield was almost doubled over the average.

Tsukomoto et al. (1976) in a field study at Brandon Manitoba found that the seed yield (kg•ha^{-1}) of lentil (1418) was lower than that of field pea (2146) and fababean (1845). On the other hand, under irrigated field conditions in southern Alberta, Rennie and Dubetz (1986) reported a lentil seed yield of 5511 kg•ha^{-1}, which was higher than that of fababean, pea and chickpea. It appears therefore, that lentil yields are often low, but they have a very high yield potential.

Lentil fixed less N_2 than other legumes, such as fababean, pea and soybean when grown under comparable conditions in growth chamber experiments (Rodd, 1986).

Bremer et. al. (1988) found that applied nitrogen increased seed yield of lentil, which is usually not the case with other field grown legumes. Walley (1986) found that small amounts of applied nitrogen increased seed yield. It was concluded that lentil was not efficient in fixing enough N_2 to meet optimum plant growth requirements in a field experiment.

Researchers have found variable responses of annual legumes to phosphorus. In the growth chamber, Lambert et. al. (1979), De Beer (unpublished data), and Singh and Singh (1986) observed yield responses in soybean and lentil and lentil respectively. In the field, in Manitoba, Bullen et. al. (1983) and Bailey and Grant (1988) observed yield responses of soybean and fababean respectively. Contrarily, Tsukomoto et. al. (1976) observed no yield response of 11 annual legumes including lentil in Manitoba to the addition of phosphorus. DeBeer (unpublished data), in field experiments in Manitoba with lentil observed no seed yield response to the addition of phosphorus, in low P sandy soils. In Saskatchewan, Bremer et. al. (1988) found a yield response to added phosphorus (0 vs. 30kgP•ha^{-1}) in one out of three sites. The sites, with high soil P and low precipitation did not show a response. This indicates that at the other sites' poor growth caused a low demand for P in the plants, and no response was observed. Other researchers observed increases in yield when larger amounts of P were added to soil (Hamdi; 1976, Israel; 1987).

At all sites used by Bremer et al. (1988), about 50% of the plant N was from N_2 fixation, thus P addition did not increase nitrogenase activity. However, in a study of the effect of P on N_2 fixation, Israel (1987) concluded that N_2 fixation had a higher P requirement for fixation to occur, than did soybean growth.

- Effect of P and VAM on N_2 fixation and growth

Vesicular-arbuscular mycorrhizae (VAM) are fungi that live in symbiotic association with most plant species' roots. The fungi aid many crop plants in the uptake of P and also of Zn and Cu (Kucey and Paul; 1983, Bolan et. al.; 1983, Thompson et. al.; 1988) and other nutrients such as N (Smith; 1980), and K (Lambert et al.; 1979). Bala and Singh (1985) observed increased lentil growth, dry matter production, nodulation and N_2 fixation following VAM inoculation in unsterile low and medium P soils in growth chamber experiments. The importance of P and VAM for N_2 fixation was stressed by Mosse et al. (1976), who determined that clover, and the tropical legumes *Stylosanthes* and *Centrosema* did not form nodules in a P deficient soil unless VAM was added. Singh and Singh (1986) found positive effects of VAM and P addition on lentil yields.

- Effect of VAM and *Rhizobium* inoculation on growth and N_2 fixation

Double inoculation of legumes with VAM and *Rhizobium* as compared to inoculation with either symbiont could be beneficial. Manjunath et. al. (1984) found dual inoculation with VAM and *Rhizobium* to be beneficial to the fodder tree legume *Leucaena*. Dual inoculation with both the organisms improved nodulation, VAM colonization, dry mass, nitrogen and phosphorus content of the plants compared to single inoculation with either organism. Daft and El-Giahmi (1974) found that double inoculation increased growth, nodule number, nodule mass per gram of root, acetylene reduction, shoot %P, shoot %N, and shoot yield of French bean grown in a growth chamber. It is however not clear if a mutualistic symbiotic relationship between the two microbes exists, which would suggest that VAM could affect yield and N_2 fixation other than by means of increasing the P content of the nodule and plant.

The effect of P addition and VAM inoculation on lentil growth was the purpose of this study. The effect of the interaction of *G. intraradices* and *Rhizobium leguminosarum* on growth of lentil was also investigated in the growth chamber.

MATERIALS AND METHODS

The Almasippi subsoil used in the growth chamber experiments was from the C horizon at a depth of 1.5 m from Haywood Manitoba. The subsoil was air dried, and sieved (2 mm). All subsoils were fine sands, contained carbonates and were low in nutrient content (NO_3-N 1.8-5.0$\mu g \cdot g^{-1}$, $NaHCO_3$ extractable P 1.2-3.0$\mu g \cdot g^{-1}$, and DTPA extractable Zn, Cu, and Mn 0.24-0.48, 0.40-0.58, and 1.1-1.6$\mu g \cdot g^{-1}$ respectively). The pH ranged from 7.7-8.4. Subsoil was used, mainly because it had no indigenous VAM in it. This eliminated the need to sterilize the subsoil, which can introduce chemical and also biological changes (Strong et al.; 1988), such as decreases or increases of $NaHCO_3$ extractable P (Stribley et al.; 1980).

The *Glomus intraradices* infected sweet corn roots (*Zea mais* var. Golden Beauty) was placed two cm below the surface sterilized (95% ethanol 10 seconds and 2% sodium hypochlorite for two minutes) lentil seeds to serve as VAM inoculum.

Growth Chamber Experiment 1, 2a, and 3a

Experiments, to determine how the dry matter yield, P and N accumulation in lentil (*Lens esculenta* var. Eston) are affected by P application and inoculation with *G. intraradices*, were conducted. Completely randomized experiments with rates of P from 0-175$\mu g \cdot g^{-1}$ and two rates of G. intraradices inoculum (+VAM and -VAM) and three repetitions were carried out. All nutrient rates were calculated on an air dried basis of the soil. The application of liquid phosphoric acid was carried out prior to seeding in all experiments. Basal nutrients were applied in $\mu g \cdot g^{-1}$ as follows. N as NH_4NO_3 at 250, S as K_2SO_4 at 50, K as K_2SO_4 at 122, K as KCl at 128, Zn as $ZnSO_4 \cdot 7H^2O$ at 5, Cu as $CuSO_4 \cdot 5H_2O$ at 2.5, Fe as $FeSO_4 \cdot 7H_2O$ at 5, Mn as $MnSO_4 \cdot H_2O$ at 2.5, B as H_3BO_3 at 0.15, and Mo as $NaMoO_4 \cdot 2H_2O$ at 0.05. In experiment 2a, the Zn, Cu, and Mo concentrations were doubled, the N was applied at $40 \mu g \cdot g^{-1}$, and the lentil were inoculated with Rhizobium leguminosarum. All pots were kept in a growth chamber in which the photoperiod was adjusted to 16 hours per day at a temperature of 15-18°C at night and 22-24°C during the day. The shoots were harvested between 61 and 64 days after seeding, at which time flowering was about 80% complete, and some pods had formed. shoots were oven dried at 60°C for 72 hours. Oven dry mass was determined of each sample. All samples were ground in a Wiley mill to pass through a 2mm sieve.

Analysis. Kjeldal nitrogen was determined, and N_2 fixation was calculated based on the ^{15}N dilution method. Plant digestion was performed in a perchloric-nitric acid mixture (Chapman and Pratt; 1961). Concentration of P in the plant tissue was determined by the molybdate-blue method (Murphy and Riley; 1962) and those of Zn, Cu, Fe, and Mn were analyzed by atomic absorption spectroscopy. Randomly selected root pieces from every pot were stained differentially, with trypan blue to reveal fungal structures, according to the method outlined by Phillips and Hayman (1970). Infection of VAM fungi was scored according to a method also used by Ocampo et al. (1980).

Experiment 2b and 3b

These experiments were conducted concurrently with the previous experiments. Their purpose was to determine if G. intraradices has a positive effect on lentil growth at high levels of added P ($175 \mu g \cdot g^{-1}$), and to determine if G. intraradices has a positive interaction effect with Rhizobium. The design was a 2x2 factorial experiment, which was completely randomized. The treatments consisted of two rates of G. intraradices inoculation (+VAM and -VAM), and two rates of Rhizobium inoculation (+Rhiz and -Rhiz). All other conditions of the experiments were as in Experiment 2a and 3a. In Experiment 3b, several pots were duplicated, which were harvested at seed maturity at 98 days after seeding and seed yield was determined.

RESULTS AND DISCUSSION

Growth Chamber Experiments 1, 2a, and 3a

In the experiments there was a significant positive shoot dry matter yield response of lentil to added P (Table 1), up to a rate of about 80 $\mu g \cdot g^{-1}$, after which the yield levelled off (Figure 1). The plants in the treatments without added P died at about 40 days, and had a very low yield and no branches. This reflected the low P status of the soil (1.2 to 3.0 $\mu gP \cdot g^{-1)}$. However, oilseed rape grown in the same experiments without added P, had a very high shoot yield ($9.6 g \cdot pot^{-1}$). This suggests that oilseed rape is much more efficiet at accumulationg P from P deficient soils, than is lentil. When plants were inoculated with G. intraradices (VAM), the shoot dry matter yield increased due to P addition at a different rate, as compared to uninoculated plants (table 1). In Experiments 1 and 3a, there was no significant yield response to 20 or 40 $\mu g \cdot g^{-1}$ of P when not inoculated with G. intraradices, whereas when inoculated, there was an increase in yield due to P at 20 and 40$\mu g \cdot g^{-1}$. Thus it appears that G. intraradices inoculated plants were able to grow in soils with a lower P status. Similar results were reported, for subterranean clover when grown on subsoil, by Bolan et.al. (1983). The apparent higher yield of Experiment 1 could be due to the addition of 250$\mu g \cdot g^{-1}$ of N, whereas the other experiments received only 40 $\mu g \cdot g^{-1}$.

Table 1. Effect of added phosphorus and inoculation with G. intraradices on shoot dry matter yield of lentil

Rate of P $\mu g \cdot g^{-1}$	Experiment 1		Experiment 2a		Experiment 3a	
	inoculation with G. intraradices					
	+	-	+	-	+	-
0	0.1 E[*] a[&]	0.08C b	-[#]	-	0.08C a	0.04B b
20	3.5 D a	0.4 C b	-	-	-	-
40	6.4 C a	4.0 BC a	2.1 B a	1.9 B a	2.4 B a	1.4 B a
60	9.9 B a	4.9 ABC b	3.9 AB a	2.3 B a	2.0 BC a	2.9 AB a
80	11.5 A a	8.8 AB a	5.2 AB a	2.4 B a	3.1 AB a	5.7 A a
100	11.3 AB a	10.0 A a	4.2 AB a	3.9 AB a	-	-
125	11.5 A a	8.5 AB a	5.8 AB a	6.4 A a	3.0 AB a	5.8 A a
150	12.6 A a	8.0 AB b	-	-	-	-
175	12.2 A a	9.5 A a	6.2 A a	3.1 AB a	5.2 A a	2.9 AB a
mean	8.8 a	6.0 b	4.5 a	3.3 a	2.6 a	3.1 a

[*] Duncans Multiple Range Test, means followed by the same uppercase letter in each column are not significantly different at p = 0.05

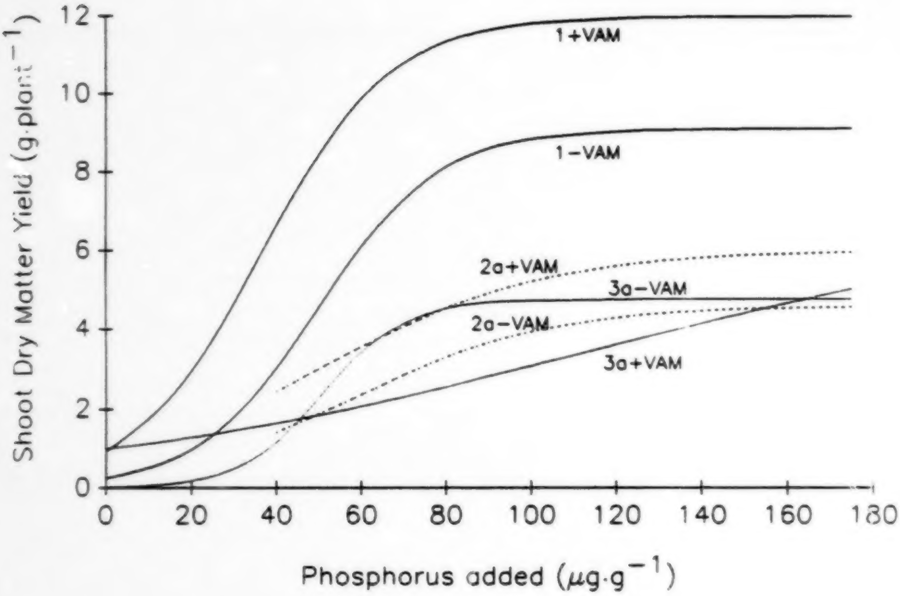
[&] Duncans Multiple Range Test, means followed by the same lowercase letter in each row within each experiment are not significantly different at p = 0.05

[#] Treatment did not exist in this experiment

All treatments in Experiment 1 had a positive yield response to G. intraradices inoculation. Experiment 2a had no significant response due to high variability within replicates, but the yield increase due to G. intraradices was 44%, which was equal to the yield increase in Experiment 1. In Experiment 3a, inoculation with G. intraradices decreased yield of the intermediate P treatments. This resulted in a 13% yield decrease due to G. intraradices inoculation. This result was not as expected based on the previous experiments.

Experiment 3a had 3% of its roots infected with VAM vesicles when not inoculated with G. intraradices. This was due to contamination. The inoculated treatments had the following average infection; Experiment 1; 62%, Experiment 2; 13% and Experiment 3; 69%. Reasons for the lower infection in Experiment 2a are not known but a lower light intensity, as was the case in Experiment 2a has been reported to

Figure 1. Effect of added phosphorus and VAM inoculation on shoot dry matter accumulation of lentil (Experiment 1, 2a and 3a).



Experiment 1+VAM $Y=11.97/(1+11.93_e(-0.067*X))$ CD=0.96
Experiment 1-VAM $Y= 9.10/(1+34.85_e(-0.071*X))$ CD=0.69
Experiment 2a+VAM $Y= 5.99/(1+ 6.71_e(-0.038*X))$ CD=0.35
Exerimentt 2a-VAM $Y= 4.58/(1+12.72_e(-0.043*X))$ CD=0.25
Experiment 3a+VAM $Y= 7.09/(1+ 6.16_e(-0.015*X))$ CD=0.58
Experiment 3a+VAM $Y= 4.75/(1+196.13_e(-0.104*X))$ CD=0.45

decrease VAM infection. If VAM infection affects yield, then G. intraradices infected treatments in Experiment 3a should have had a high yield. In Experiment 2a, the VAM infection was low, i.e. 13%, as compared to 67% and 69% in Experiment 1 and 3a respectively, but the yield increase due to G. intraradices was 44%. The non G. intraradices treatments in experiment 3a, VAM was observed as contamination at 3%, and these treatments had a reasonable yield. It appears, that VAM can cause yield increases at low infection levels, but at high infection, it might be damaging to the plant, as it uses energy from the plant to sustain its life. Sometimes a decrease in plant growth during the early establishment phase of infection is observed, presumably due to nutrient removal from the host (Baylis; 1975, Volkmar; 1981, Smith; 1980).

Percent Phosphorus in Shoot

In Experiment 1, the non G. intraradices roots were P deficient at the low rates of added P (Mengel and Kirkby; 1982) (Table 2). In all three experiments the average shoot percent P was higher when inoculated with G. intraradices, but the main effects were only significant in Experiment 1 and 3a. Thus G. intraradices inoculation increased P availability. The mean shoot %P increased from Experiment 1 to 2a to 3a (Table 2), however as the concentration increased, the shoot dry matter yield decreased (Table 1). This inverse relationship between shoot P concentration and yield, could be attributed to P dilution, with increasing yield. Thus the absolute shoot %P and %VAM infection could not be used to predict the benefits of G. intraradices inoculation. However, the P uptake (Table 3), in Experiment 1 was 79% higher than Experiment 2a, and 84 % higher than in Experiment 3a. Inoculation with G. intraradices had a direct positive effect in Experiment 1, because

Table 2. Effect of added phosphorus and inoculation with G. intraradices on shoot percent phosphorus of lentil

	Experiment					
	1		2a		3a	
Rate of P µg•g^{-1}	inoculation with G. intraradices +	-	+	-	+	-
0	0.088 F[*] a[&]	0.094 D a	-[#]	-	x[$]	x
20	0.145 E a	0.126 BC a	-	-	-	-
40	0.161 CDE a	0.118 CD b	0.144 D a	0.142 B a	0.237 A a	0.151 D b
60	0.154 DE a	0.120 BCD b	0.158 CD a	0.150 B a	0.258 A a	0.188 C b
80	0.166 BCD a	0.150 ABC a	0.186 BC a	0.193 A a	0.252 A a	0.205 BC b
100	0.176 BC a	0.151 AB a	0.203 B a	0.204 A a	-	-
125	0.186 AB a	0.150 ABC b	0.215 B a	0.225 A a	0.266 A a	0.244 A a
150	0.197 A a	0.142 ABC b	-	-	-	-
175	0.205 A a	0.169 A a	0.264 A a	0.217 A b	0.264 A a	0.229 AB a
mean	0.164 a	0.136 b	0.195 a	0.189 a	0.255 a	0.204 b

(Note removed one sample of .123% from Experiment 3a +VAM 125P, before mean was .218%)

[*] Duncans Multiple Range Test, means followed by the same uppercase letter in each column are not significantly different at p = 0.05

[&] Duncans Multiple Range Test, means followed by the same lowercase letter in each row within each experiment are not significantly different at p = 0.05

[#] Treatment did not exist in this experiment
[$] Treatment was not analyzed due to lack of plant material

both the P concentration and uptake increased, but this was not the case in the other experiments.

Table 3. Effect of added phosphorus and inoculation with G. intraradices on shoot phosphorus uptake in lentil shoots (mg P per plant)

Rate of P $\mu g \cdot g^{-1}$	Experiment 1		Experiment 2a		Experiment 3a	
	inoculation with G. intraradices					
	+	-	+	-	+	-
0	0.1 G* a&	0.1 C a	-#	-	x&	x
20	5.1 F a	0.6 C b	-	-	-	-
40	10.3 E a	4.8 BC b	3.0 C a	2.8 B a	5.3 B a	2.2 B a
60	15.3 D a	5.9 BC b	6.3 BC a	3.4 B a	5.0 B a	5.4 AB a
80	19.1 C a	13.1 AB b	9.8 ABC a	4.7 B a	7.7 AB a	11.6 AB a
100	19.9 BC a	15.7 A a	8.5 ABC a	8.1 AB a	-	-
125	21.2 B a	13.0 AB a	12.9 AB a	14.4 A a	6.2 B a	14.3 A a
150	24.8 A a	11.5 AB b	-	-	-	-
175	24.9 A a	17.1 A a	16.3 A a	6.8 B a	13.6 A a	6.7 B a
mean	15.6 a	9.1 b	9.5 a	6.7 a	7.7 a	8.0 a

* Duncans Multiple Range Test, means followed by the same uppercase letter in each column are not significantly different at $p = 0.05$

& Duncans Multiple Range Test, means followed by the same lowercase letter in each row within each experiment are not significantly different at $p = 0.05$

# Treatment did not exist in this experiment

Nitrogen fixation

In Experiment 1, no nodules were observed on the roots unless at least 40 $\mu g \cdot g^{-1}$ of P were added in the G. intraradices treatments, and $80 \mu g \cdot g^{-1}$ of P were added ,in the non G. intraradices treatments (Table 4). Thus nodulation did not occur, when the shoot P concentration was below about 0.14%. In general, the nodule size increased, when more P was added, and the shoot P concentration increased. In Experiment 2a and 3a, when $40 \mu g \cdot g^{-1}$ of P were added, all treatments had nodules, and the shoot P concentration was above 0.14% in all plants. Moose (1977) found that stylosanthes containing less than 0.1% P did not nodulate. Thus there exists a critical shoot P concentration, below which nodulation will not occur. In Experiment 1, G. intraradices inoculation improved shoot %P, so that nodulation could occur in low P added treatments. Inoculation with G. intraradices resulted in an increase of 43% and 29% of nodule number and % N derived from the atmoshpere (%NdfA) respectively in Experiment 2a (Table 4). In Experiment 3a, there was only a trend in the same direction. When less than $60 \mu g \cdot g^{-1}$ of P were added, the nodule number and %NdfA were relatively low. The %NdfA was the highest in the G. intraradices inoculated, $175 \mu g \cdot g^{-1}$ P treatment in Experiment 3a, which was 82% and had a high yield. The %NdfA was higher in Experiment 3a, while the shoot yield was lower. Within each experiment, there exists a linear regression between the %NdfA as well as the shoot %N and the dry matter yield. The coefficient of determination was; Experiment 2a +VAM 0.92, -VAM 0.76, Experiment 3a +VAM 0.65, -VAM 0.83. Thus since G. intraradices inoculation increases N_2 fixation, which affects yield, G. intraradices also increases yield.

Table 4. Effect of added phosphorus and inoculation with *G. intraradices* on nodule number, percent nitrogen derived from atmosphere (%NdfA) and shoot nitrogen percent in lentil shoots

Experiment	nodules (per plant)		%NdfA		shoot % N	
Rate of P	inoculation with *G. intraradices*					
	+	-	+	-	+	-
Experiment 1						
0	none	none			x[$]	x
20	none	none			3.38 A	x
40	in 1 pot	none			2.57 B b	3.08 A a
60	present	none			2.23 C b	2.75 A a
80	present	present	not determined		1.97 CD a	2.36 A a
100	present	present			2.20 CD a	2.31 A a
125	present	present			2.08 CD a	2.43 A a
150	present	present			1.93 D a	2.37 A a
175	present	present			2.19 CD a	2.39 A a
mean					2.32 b	2.53 a
Experiment 2a						
40	83 A a	50 D a	41 A a	31 B a	1.75 A a	1.78 A a
60	87 A a	53 CD a	52 A a	32 B a	1.70 A a	1.42 A a
80	132 A a	74 BCD a	72 A a	37 AB a	2.01 A a	1.53 A b
100	149 A a	98 BC a	65 A a	58 AB a	1.84 A a	1.75 A a
125	159 A a	157 A a	76 A a	72 A a	1.93 A a	1.93 A a
175	150 A a	101 B a	69 A a	58 A a	1.90 A a	1.78 A a
mean	127 a	89 b	62 a	48 b	1.86 a	1.70 a
Experiment 3a						
0	3 B a	0 C b	x	x	x	x
40	43 AB a	22 ABC a	66 AB a	48 A a	2.58 A a	2.22 A b
60	24 AB a	14 BC a	54 B a	60 A a	2.20 B a	2.16 A a
80	69 A a	62 AB a	69 AB a	71 A a	2.41 AB a	2.21 A a
125	31 AB a	69 A a	67 AB a	73 A a	2.18 B a	2.22 A a
175	69 A a	50 ABC a	82 A a	57 A a	2.39 AB a	1.75 A b
mean	40 a	36 a	67 a	62 a	2.35 a	2.11 b

[*] Duncans Multiple Range Test, means followed by the same uppercase letter in each column within each experiment are not significantly different at $p = 0.05$

[&] Duncans Multiple Range Test, means followed by the same lowercase letter in each row are not significantly different at $p = 0.05$

[$] Treatment was not analyzed due to lack of plant material

In Experiment 2a and 3a, the *G. intraradices* plants had an increase in N concentration over the non *G. intraradices* plants. There was never any change in N concentration due to addition of P, except in the non VAM plants in Experiment 1, where the N concentration decreased, with increasing increments of added P, most likely due to dilution,

Growth Chamber 2b and 3b

The interaction effects of *Rhizobium* and *G. intraradices* were tested. The shoot yield of lentil in Experiment 2b increased due to inoculation with either organism. (Table 5). In Experiment 2b and 3b, when inoculated with both symbiants, the increase was larger. The shoot P concentrations increased due to *G. intraradices* inoculation in

Table 5. The effect of G. intraradices (VAM) and R. leguminosarum (Rhiz) inoculation on lentil growth

Experiment 2b

Treatment	Shoot yld $g\cdot plant^{-1}$	Shoot %P	%VAM inf.	Shoot N $mg\cdot plant^{-1}$	%N fixed
-Rhiz -VAM	2.0 b	0.22 b	0	20 b	0 b
-Rhiz +VAM	2.9 b	0.26 a	4	46 ab	42 ab
+Rhiz -VAM	3.1 b	0.22 b	0	57 ab	68 a
+Rhiz +VAM	6.2 a	0.26 a	2	129 a	69 a

Treatment	Shoot Zn		Shoot Cu	
	$\mu g\cdot g^{-1}$	$mg\cdot plant^{-1}$	$\mu g\cdot g$-1	$mg\cdot plant^{-1}$
-Rhiz -VAM	44 b	87 b	6.0 b	12 b
-Rhiz +VAM	68 a	196 ab	9.0 a	26 ab
+Rhiz -VAM	22 c	73 b	5.0 b	16 b
+Rhiz +VAM	39 b	252 a	9.2 a	62 a

Experiment 3b

Treatment	Shoot yld $g\cdot plant^{-1}$	Shoot %P	%VAM inf.	Shoot N $mg\cdot plant^{-1}$	%N fixed
-Rhiz -VAM	4.3	0.27	2	100	66
-Rhiz +VAM	2.3	0.25	59	40	39
+Rhiz -VAM	2.9	0.23	1	50	57
+Rhiz +VAM	5.2	0.26	48	130	82

*all pots received N at $40\mu g\cdot g^{-1}$ and P at $175\mu g\cdot g^{-1}$

Experiment 2b, although the VAM infection was very low. N_2 fixation also increased due to G. intraradices inoculation, as was observed by Manjunath et. al. (1984) and Daft and El-Giahmi (1974). The Zn and Cu concentration and uptake increased due to G. intraradices inoculation in Experiment 2b. The seed yield in Experiment 3b increased due to G. intraradices inoculation, and also due to added P (Table 6). This seed yield increase was observed, although the inoculation of G. intraradices was negative on the vegetative shoot yield in this experiment.

Table 6. The effect of P addition and G. intraradices inoculation on lentil shoot and seed yield (Experiment 3b)

	Seed yield ($g\cdot plant^{-1}$)		Vegetative shoot yield ($g\cdot plant^{-1}$)	
	Level of added P		Level of added P	
	$40\mu g\cdot g^{-1}$	$125\mu g\cdot g^{-1}$	$40\mu g\cdot g^{-1}$	$125\mu g\cdot g^{-1}$
-VAM	0.6	2.3	1.4	5.8
+VAM	1.7	3.1	2.4	3.0

*all pots received N at $40\mu g\cdot g^{-1}$

Conclusions

In growth chamber experiments using P deficient sandy subsoil, lentil vegetative shoot yield increased to P application. The lentil in the no P added treatments died, however, oilseed rape under the same condition had a high yield. Thus rapeseed is able to accumulate P better from low P soils than is lentil. Lentil yield also increased by 44% to VAM inoculation, when no contamination of VAM occured in the non VAM treatments. Lentil yield increased due to double inoculation with *Rhizobium* and *G. intraradices* (VAM) at a greater rate than when the plants were inoculated with either organism. Thus VAM seems to increase N_2 fixation. Lentil seed yield increased, due to VAM inoculation and P addition, even when vegetative yield did not increase.

The authors would like to acknowledge the financial assistance of the Natural Sciences and Engineering Research Council of Canada.

LITERATURE CITED

Bailey, L.D. and C.A. Grant. 1988. Pulse crop production: Soybeans and fababeans on the prairies. Review of Results 1988. Agriculture Canada research station Brandon Man. pp.66-67.

Bala, S. and O.S. Singh. 1985. Response of lentil to VA Mycorrhizal inoculation and plant available P levels off unsterile soils. Plant Soil. 87:445-447.

Baylis, G.T.S. 1975. The magnolioid mycorrhiza and mycotrophy in root systems derived from it. In *Endomycorrhizas*. Eds. F.E. Sanders, B. Mosse and P.B. Tinker. Academic Press London. pp. 373- 389.

Bolan, N.S., A.D. Robson and N.J. Barrow. 1983. Plant and soil factors including mycorrhizal infection causing sigmoidal response of plants to applied phosphorus. Plant and Soil. 73: 187-201.

Bremer, E., R.J. Rennie amd D.A. Rennie. 1988. Dinitrogen fixation of lentil, field pea and fababean under dryland conditions. Can. J. Soil Sci. 68: 553-562.

Bullen, C.W., R.J. Soper, and L.D. Bailey. 1983. Phosphorus nutrition of soybeans as affected by placement of fertilizer phosphorus. Can. J. Soil Sci. 63:199-210.

Chapman, H.D. and P.F. Pratt. 1961. Methods of analysis for soils and plants and waters. University of California

Daft, M. J. and A.A. El-Giahmi. 1974. Effect of *Endogone* mycorrhiza on plant growth. New Phytol. 73:1139-1147.

Hamdi, Y.A. 1976. Field and greenhouse experiments in the response of legumes in egypt to inoculation and fertilisers. Edited by P.S. Nutman. Cambridge University Press.

Israel, D.W. 1987. Investigation of the role of phosphorus in symbiotic dinitrogen fixation. Plant Physiol. 84: 835-840.

Kucey, R.M.N. and E.A. Paul. 1983. Vesicular arbuscular mycorrhizal spore populations in various Saskatchewan soils and the effect of inoculation with *Glomus mosseae* on faba bean growth in greenhouse and field trials. Can. J. Soil Sci. 63: 87-95.

Lambert, D.H., D.E. Baker and H. Cole Jr. 1979. The role of mycorrhizae in the interactions of phosphorus with zinc, copper, and other elements. Soil Sc. Soc. Am. J. 43:976-980.

Manjunath, A., D.J. Bagyaraj and H.S. Gopala Gowda. 1984. Dual inoculation with VA mycorrhiza and rhizobium is beneficial to leucaena. Plant Soil. 78:445-448.

Mengel, K. and E.A. Kirkby. 1982. Principles of plant nutrition. Third edition. Printed by: 'Der Bund' AG Bern Switzerland.

Mosse, B. 1977. Plant growth responses to vesicular-arbuscular mycorrhiza. X.Responses of stylosanthes and maize to inoculation in unsterile soils. New Phytol. 78:277-288.

Mosse, B., C.Ll. Powell and D.S. Hayman. 1976. Plant growth responses to vesicular-arbuscular mycorrhiza. IX. Interactions between VA mycorrhiza, roch phosphate and symbiotic nitrogen fixation. New Phytol. 76:331-342.

Murphy, G. and I.A. Riley. 1962. A modified single solution method for determination of phosphate in natureal waters. Anal. Chem. Acta. 27: 31-36.

Ocampo, J.A., J. Martin and D.S. Hayman. 1980. Influence of plant interactions on VAM infections in host and non host plants grown together. New Phytol. 84: 27-35.

Phillips, J.M. and D.S. Hayman. 1970. Improved procedures for clearing roots and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assesment of infection. Transactions British Mycological Society. 55: (1) 158-160.

Rodd, V. 1986. Effect of nitrogen addition on yield and symbiotic dinitrogen fixation of Maple Amber soybeans, Aladin fababeans and lentils. M.Sc. Thesis, University of Manitoba.

Singh, O.S. and R.S. Singh. 1986. Effects of phosphorus and *Glomus fasciculatus* inoculation on nitrogen fixation, phosphorus uptake and yield of lentil (*Lens culinaris* medic) grown on an unsterilized sandy soil. Environmental and Experimental Botany. 26: (2) 185-190).

Smith, T.F. 1980. The effect of crop rotation on the abundance of spores of VAM endophytes. Plant Soil. 57:475-479.

Strong, W.M., J.P. Thompson and J.E. Cooper. (1988). Role of VAM in accessing residual fertiliser phosphorus. Vesicular-arbuscular mycorrhizae in agriculture and horticulture. Proceedings of Symposium Toowoomba Australia, 12-13 October, 1988.

Thompson, J.P., T.G. Clewett and M.L. Fiske. 1988a. Role of VAM in long fallow disorder and cropping systems. Vesicular-arbuscular mycorrhizae in agriculture and horticulture. Proceedings of Symposium Toowoomba Australia, 12-13 October, 1988.

Tsukomoto, J.Y., M. Archambault, and L.D. Bailey. 1976. Phosphate trials with annual legumes. Proc. MSSS meeting U of Manitoba. Dec 8,9 1976. pp.180-190.

Volkmar, K.M. 1981. The influence of endomycorrhizal infection and soil temperature on the growth and survival of barley roots. M.Sc. Thesis, University of Manitoba.

Walley, F.L. 1986. The effect of nitrogen and moisture availability on growth and symbiotic nitrogen fixation in lentils (Lens culinaris). M.Sc. Thesis, University of Manitoba.

Witcombe, J.R. and W. Erskine. 1984. Genetic resources and their exploytation: Chickpeas, faba beans and lentils. Martinus Nijhoff. Dr. W. Junk Publishers. Boston.